The computed quarterly piezometric heads from the calibrated model were used for the subsidence calibration. Volume compressibility values at (sand + clay) cells were assumed to be 1/2 of clay cells in the aquifer unit. For BC clay, logarithmic average values of *mv* analyzed by an interval of 5m depth were input to the model. The ratios of *mv / mv'* were input based on the typical values from the consolidation tests.

As a result, the computed land subsidence was reasonably simulated without modifying the initial input parameters. Figure 7.3.15 shows the simulated compression from 1983 to 1992. Higher compression more than 0.6 cm/m can be found in BSC and BK layers. The compression in the upper portion of BSC layer is small because the top of the layer is assigned as the constant head boundary. The compression values are controlled by not only the volume compressibility but also the changes in piezometric head. Therefore, the simulated compression in BK layer is larger than that in BSC layer. The compression in PD and NL layers ranges from 0.1 cm/m to 0.4 cm/m. The maximum compression in NB and SK layers does not exceed 0.2 cm/m. The compression more than 0.1 cm/m cannot be seen from PT to PN layers.

Figure 7.3.16 shows the results of land subsidence simulation. The simulated maximum land subsidence from 1983 to 1992 is 52.1 cm at near Minburi, Bangkok (Column No. = 27). At Site-A, the simulated land subsidence is 44.9 cm for the period. The values of total subsidence mainly depend on the compression of BSC and BK layers. The simulated land subsidence at Site-A over time is shown in the lower graph of Figure 7.3.16. The compression of BSC and BK layers occupies 48% of the total subsidence, that is almost the same ratio as the actual value.

7.3.10 Predictions

(1) Future pumpage

The future pumpage data for the period from 1993 to 2017 by Scenario 1 and Scenario 7 were arranged for the model to predict future behavior of the model. The two (2) scenarios were selected to compare future piezometric heads and land subsidence for the worst scenario (Scenario 1) with those of the best scenario (Scenario 7). The quarterly pumpage were computed by using QGPC. The pumpage values were distributed to the model cells by the method mentioned in Section 7.3.9.

(2) Scenario 1

The simulated piezometric heads in 1997, 2007, and 2017 are shown in Figure 7.3.17. The piezometric heads become deeper year by year. In 1997, the piezometric heads below -60 masl are distributed in NL and NB layers at Minburi, Bangkok. After 10 years, the piezometric heads from PD to NB layers range from -80 masl to -90 masl at Minburi area. The simulated piezometric heads in 2017 show below -120 masl near Minburi and the areas having below -60 masl in piezometric head are located from Samut Prakan to Pathum Thani. The center of the depression is located in NL and NB layers, however, the piezometric heads in BK layer also decline below -80 masl near Site-A, Lat Krabang.

The simulated compression for the 25-years period is shown in Figure 7.3.18. The maximum compression of 2.6 cm/m for the period is predicted in BSC layer at Lat Krabang area. The significant soil compression more than 1 cm/m for the period occurs at BSC and BK layers. The compression of clayey soils in PD layer ranges from 0.2 cm/m to 0.6 cm/m. The compression of clayey soils in NL and NB layers is smaller than that of upper layers due to the small volume compressibility, however, it ranges from 0.1 cm/m to 0.2 cm/m for the period. The soil compression more than 0.1 cm/m for the period occurs even in SK layer.

The simulated land subsidence along the model line by layer from 1993 to 2017 is presented in Figure 7.3.19(a). The compression in BSC layer ranges from 10 cm to 30 cm from Minburi to Lat Krabang area. The contribution of BSC layer is greater in Lat Krabang area because the thickness of BSC layer is more than 20 m in the area. However, by Scenario 1, the compression of BK and PD layers occupy about 50% of the total land subsidence. The percentage is higher than that of the historical calibration, indicating that the extreme drops of piezometric heads in main aquifers will cause significant compression in those clayey layers.

Figure 7.3.19(b) shows the total land subsidence at Site-A for the prediction period. The total subsidence will be 95.0 cm by the year 2017, consisting of 31.5 cm by BSC layer, 19.0 cm by BK layer, 22.9 cm by PD layer, 10.2 cm by NL layer, etc.

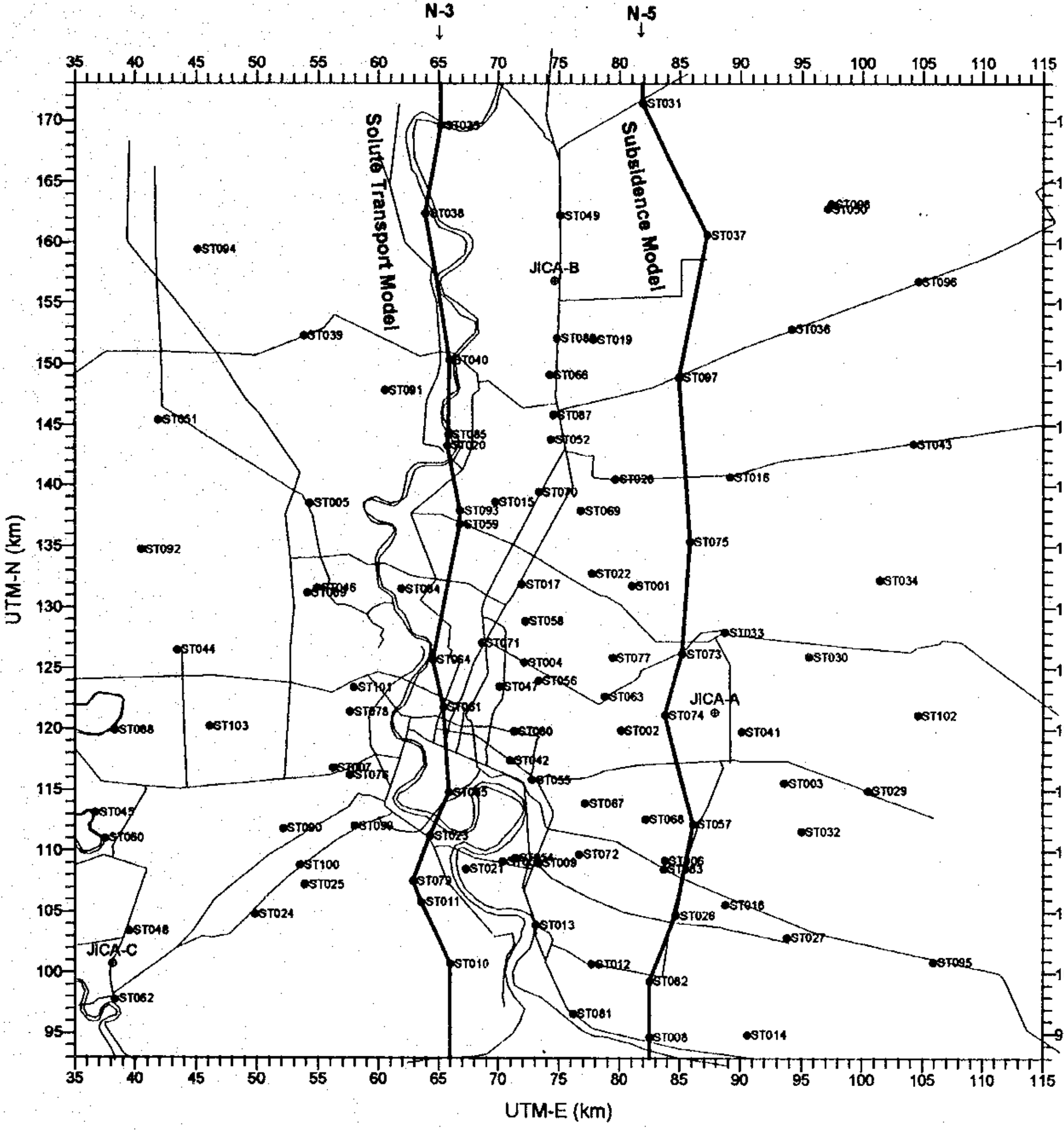
(3) Scenario 7

The simulated piezometric heads in 1997, 2007, and 2017 are shown in Figure 7.3.20. The piezometric heads will recover year by year. In 1997, the piezometric heads below -60 masl are distributed in NL layer and part of PD and NB layers at Minburi, Bangkok. After 10 years, the piezometric heads below -60 masl disappears and the area below -50 masl becomes narrower. In 2017, the heads below -40 masl occur from Minburi to Lat Krabang area, distributed only in PD, NL, and NB layers.

The simulated compression for the 25-years period is shown in Figure 7.3.21. The soil compression will occur mainly in BSC layer. The maximum compression of 1.0 cm/m for the period is predicted in BSC layer at Lat Krabang area. The compression of clayey soils in BK layer ranges from 0.1 to 0.6 cm/m. The compression in PD layer can be controlled mostly within 0.2 cm/m. The soil compression below NL layer will be less than 0.1 cm/m for the period.

The simulated land subsidence along the model line by layer from 1993 to 2017 is presented in Figure 7.3.22(a). The total land subsidence can be controlled within 26 cm for the prediction period. However, by Scenario 7, the contribution of BSC layer occupy more than 50% of the total land subsidence in Lat Krabang area.

Figure 7.3.22(b) shows the total land subsidence at Site-A for the prediction period. The total subsidence will be 24.3 cm by the year 2017, consisting of 14.5 cm by BSC layer, 1.3 cm by BK layer, 5.5 cm by PD layer, 2.4 cm by NL layer, etc. The graph indicates that the compression below BK layer will almost stop after 2005, however, the compression of BSC layer will continue up to 2017, occupying 60% of the total subsidence in 2017. The compression of BSC layer can be explained by the seasonal fluctuation of piezometric head and the consolidation characteristics of BSC layer.



LEGEND

━━ Location of Vertical Model

N-3 Hydrogeologic Profile No.

⊕ Location of JICA Monitoring Station

● Location of DMR Monitoring Station with Station No.

Figure 7.3.1	**LOCATION OF VERTICAL 2-D MODELS**
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

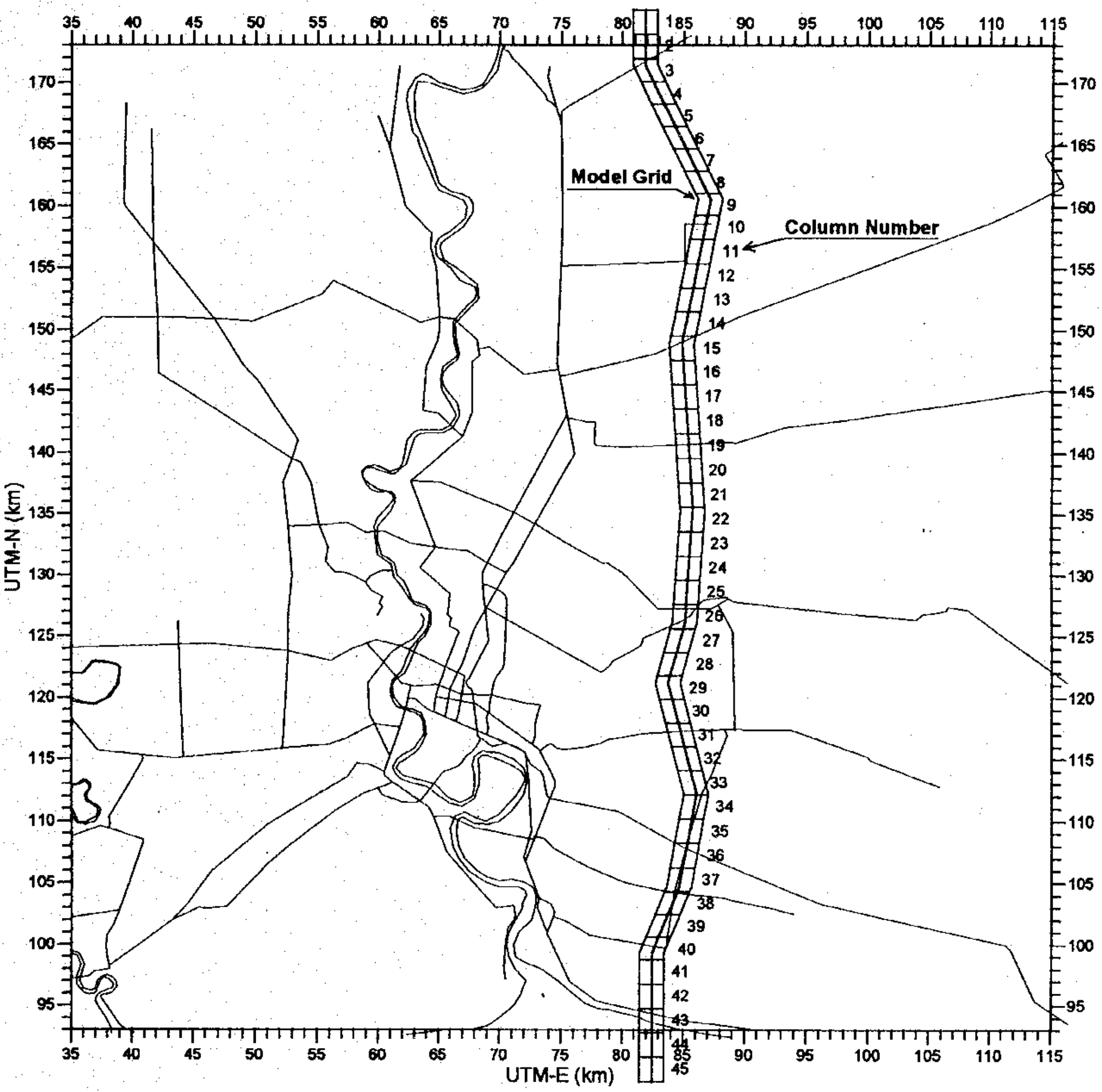


Figure 7.3.2 LOCATION OF VERTICAL 2-D LAND SUBSIDENCE MODEL

THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY

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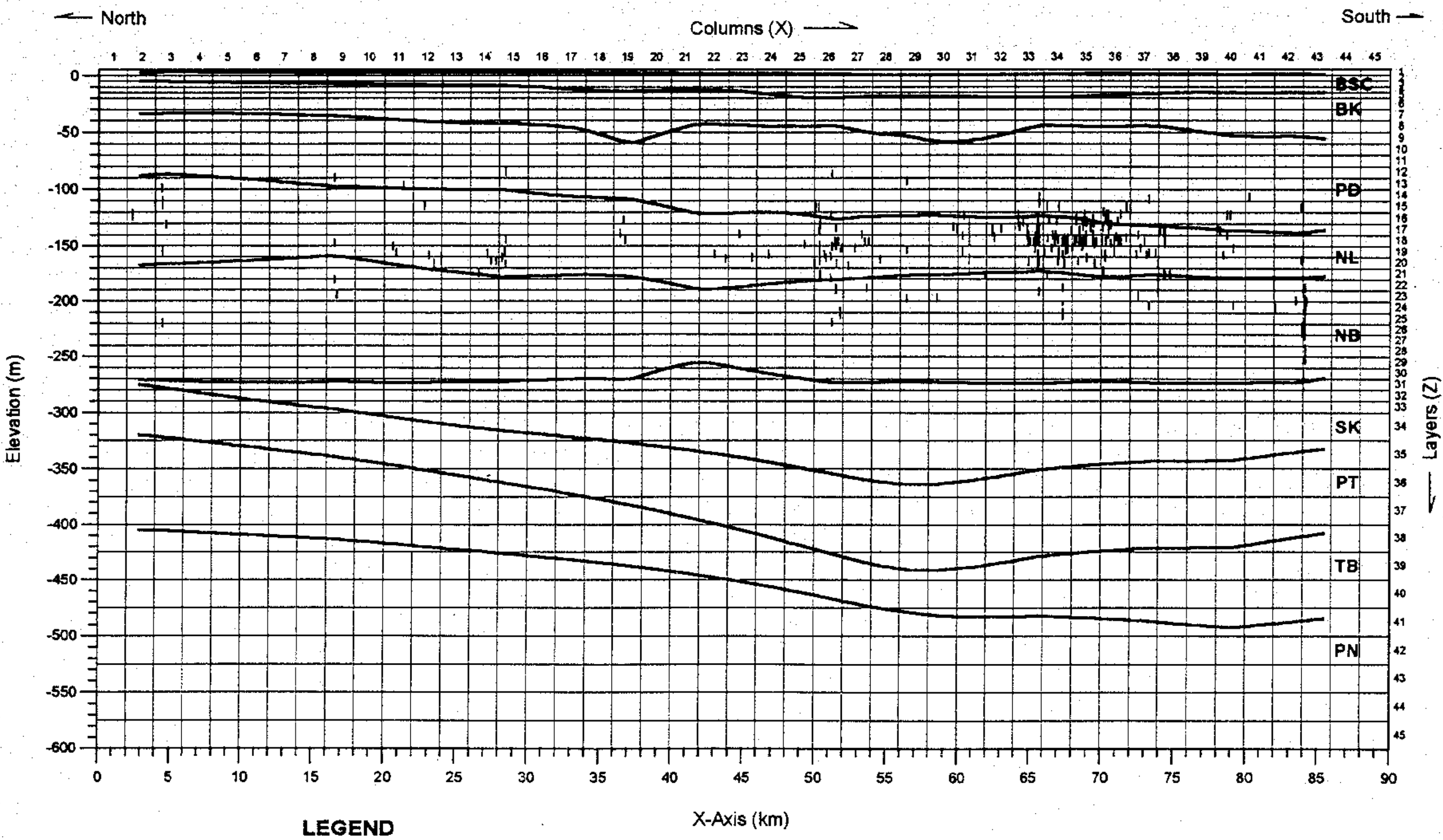


Figure 7.3.3 VERTICAL 2-D LAND SUBSIDENCE MODEL GRID

THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY

JAPAN INTERNATIONAL COOPERATION AGENCY (JICA) | KOKUSAI KOGYO CO., LTD.

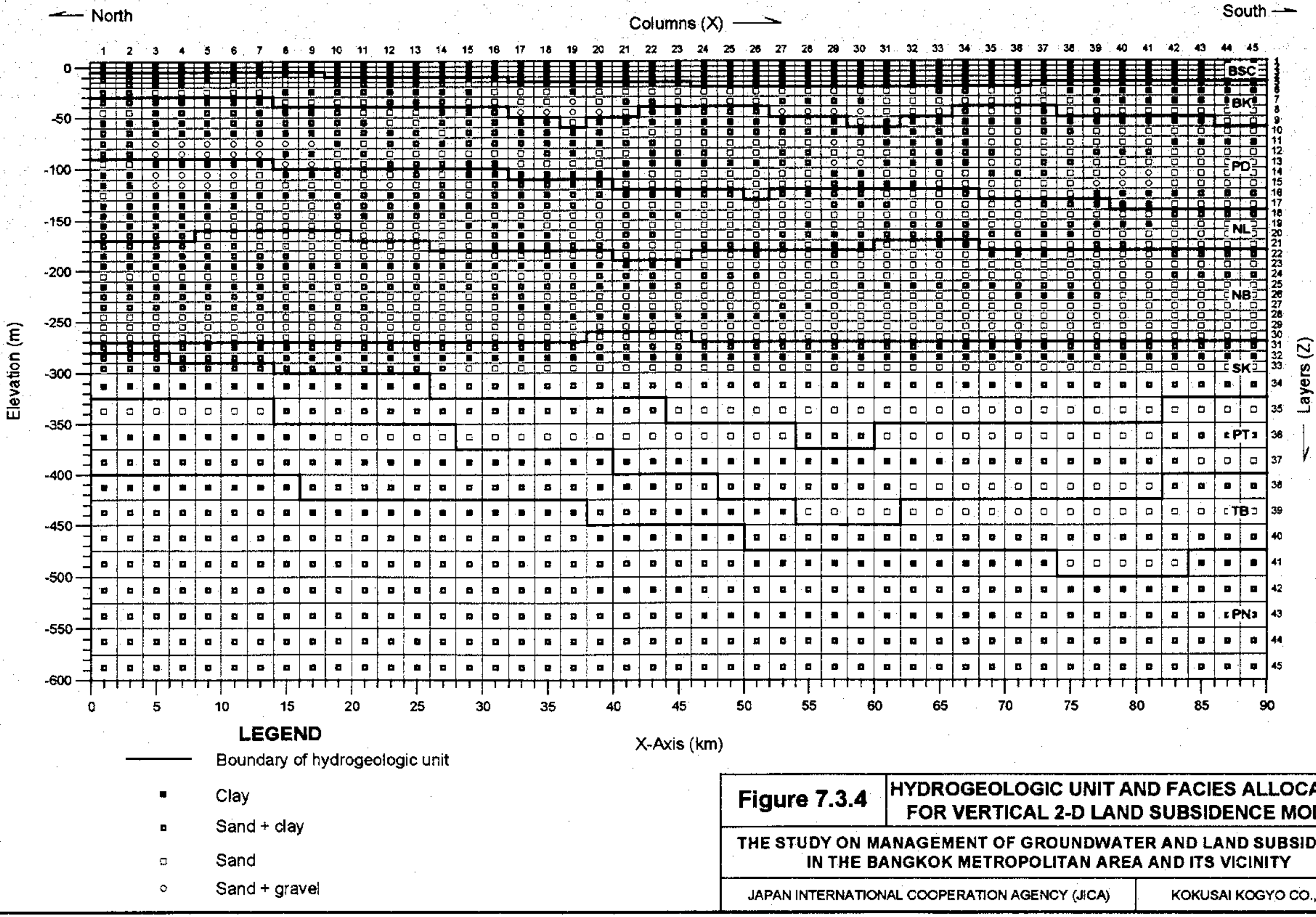
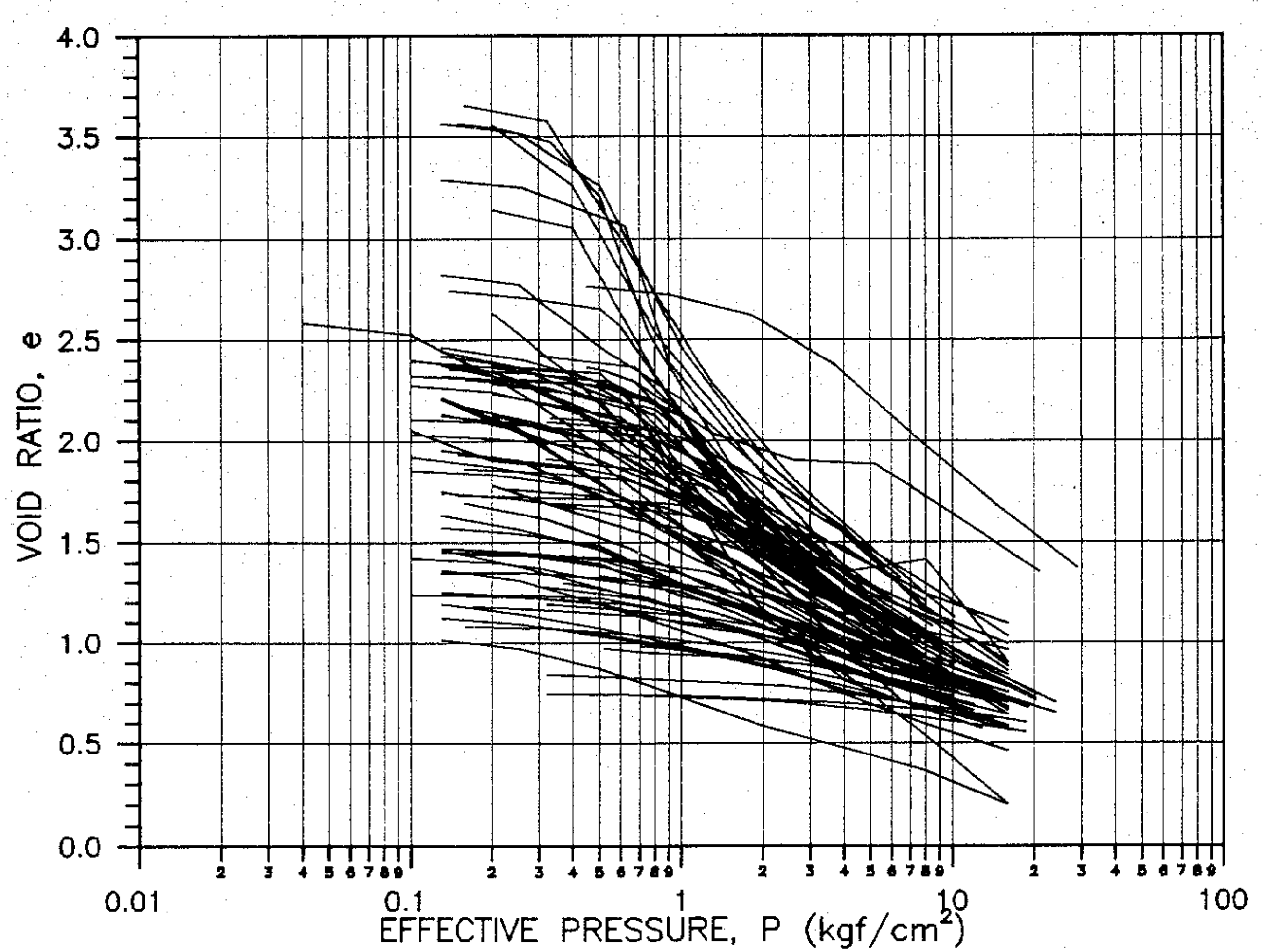


Figure 7.3.4 HYDROGEOLOGIC UNIT AND FACIES ALLOCATION FOR VERTICAL 2-D LAND SUBSIDENCE MODEL

THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY

JAPAN INTERNATIONAL COOPERATION AGENCY (JICA) | KOKUSAI KOGYO CO., LTD.

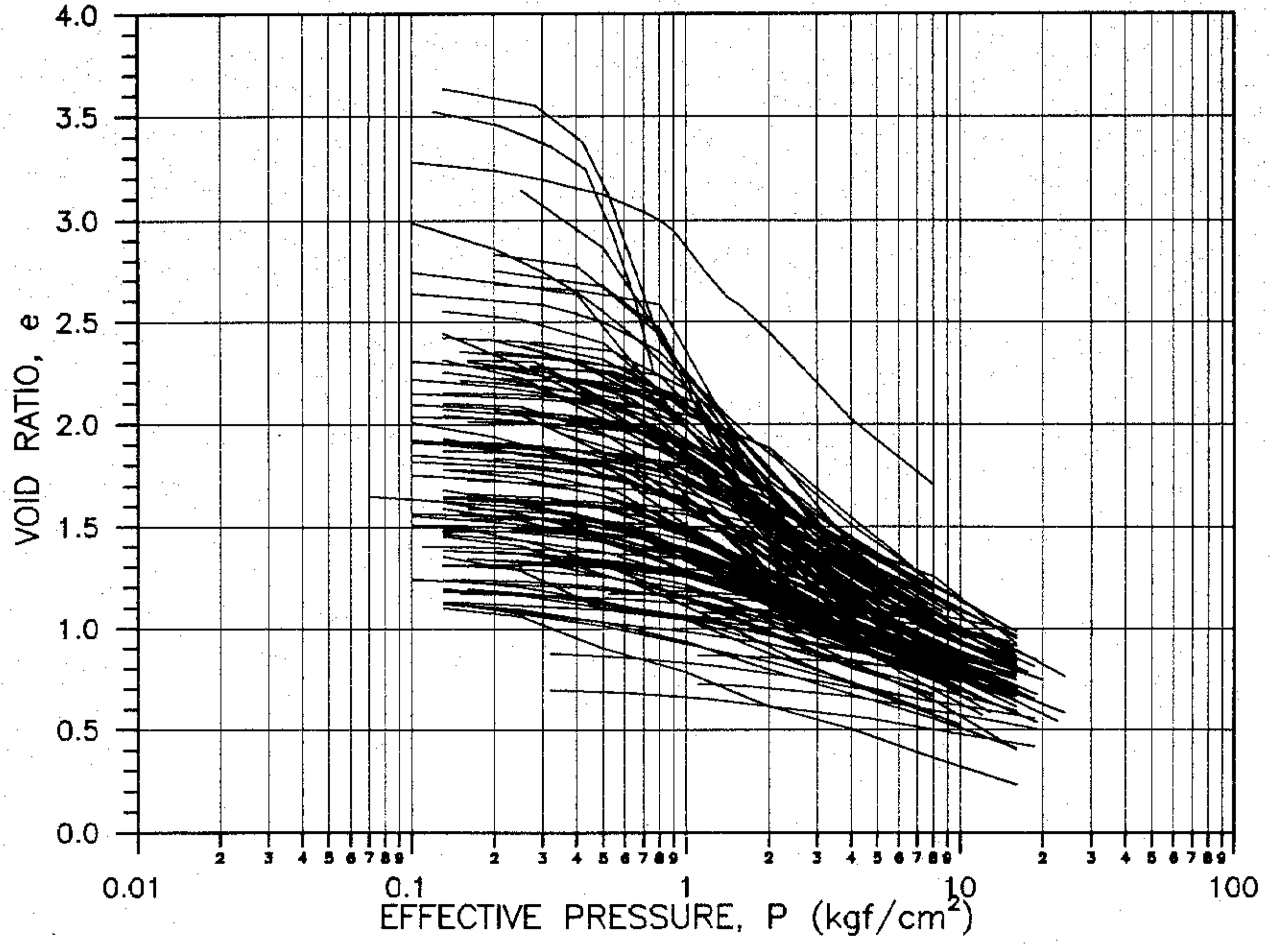


Data source: AIT(1978), Results of Laboratory Tests on Subsoils of Bangkok and Adjacent Areas, Appendix III, Volume 1.
AIT(1978), Subsurface Soil Characteristics of Bangkok and Adjacent Areas, Volume 1, 2.

Figure 7.3.5	e–logP CURVES OF CALYEY SOILS (DEPTH = 0.0m to 5.0m)

THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY

JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



Data source: AIT(1978), Results of Laboratory Tests on Subsoils of Bangkok and Adjacent Areas, Appendix III, Volume 1.
AIT(1978), Subsurface Soil Characteristics of Bangkok and Adjacent Areas, Volume 1, 2.

Figure 7.3.6	**e–logP CURVES OF CALYEY SOILS (DEPTH = 5.0m to 10.0m)**

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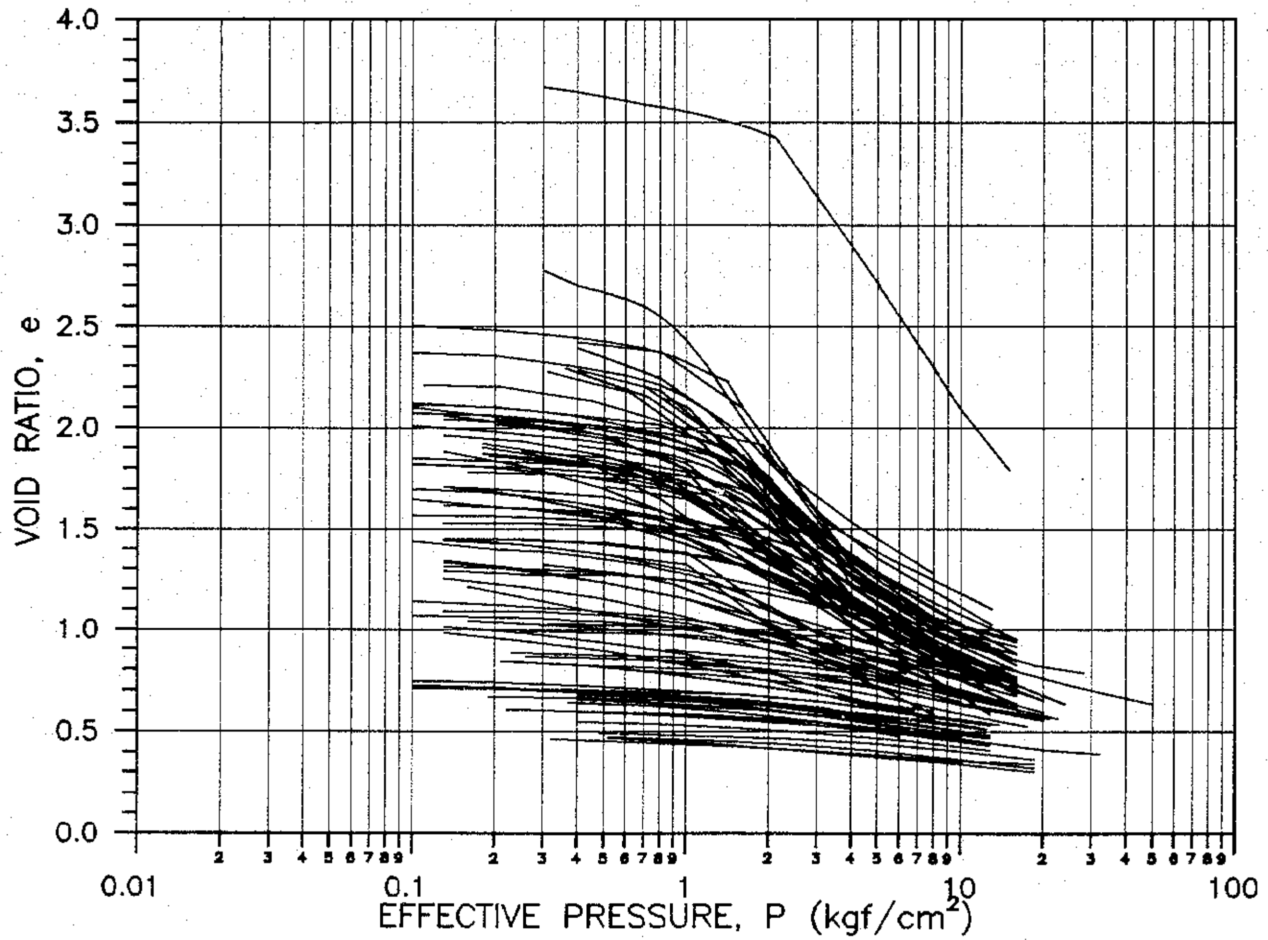

Data source: AIT(1978), Results of Laboratory Tests on Subsoils of
Bangkok and Adjacent Areas, Appendix III, Volume 1.
AIT(1978), Subsurface Soil Characteristics of
Bangkok and Adjacent Areas, Volume 1, 2.

Figure 7.3.7 e–logP CURVES OF CALYEY SOILS (DEPTH = 10.0m to 15.0m)

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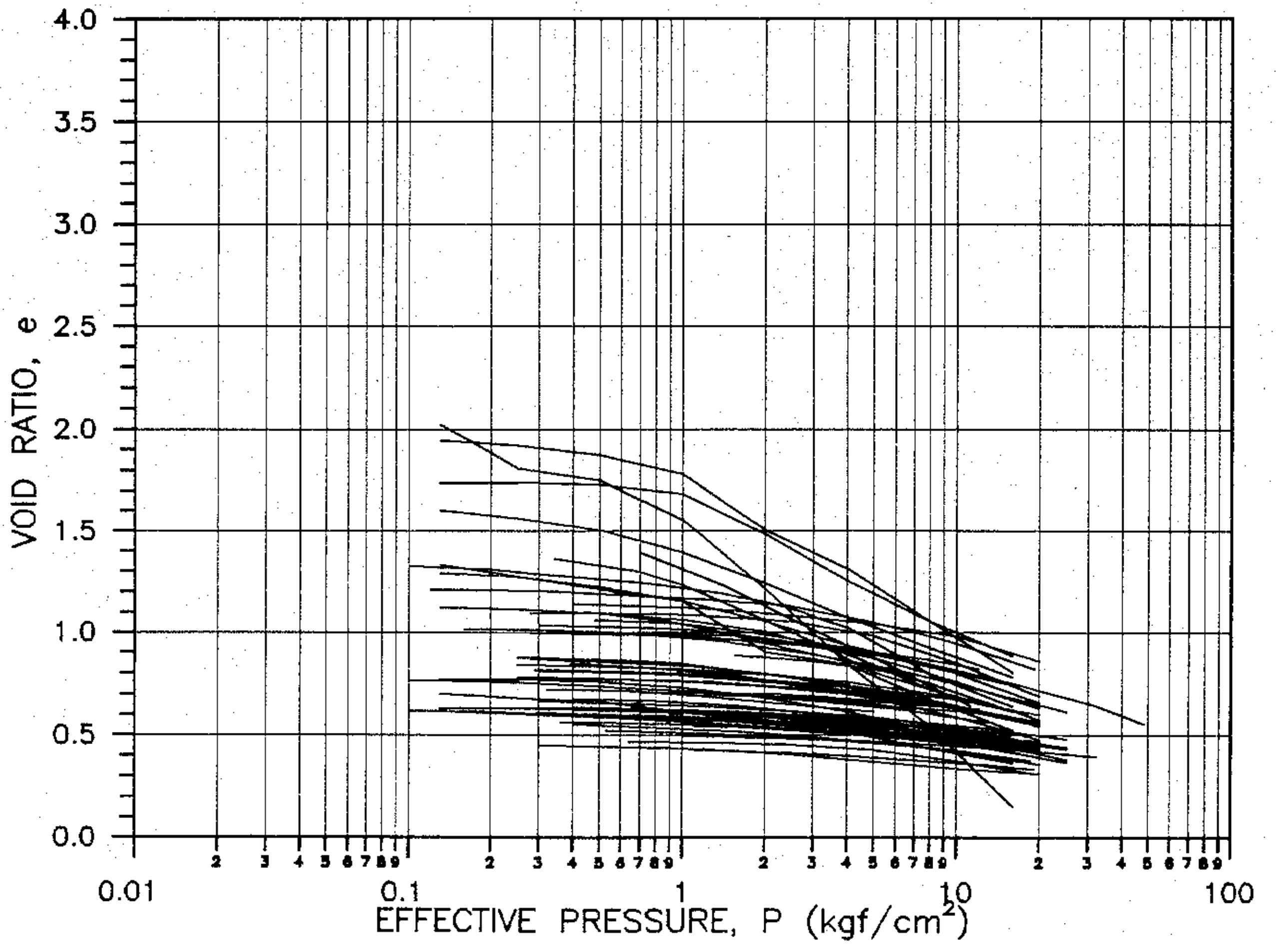

Data source: AIT(1978), Results of Laboratory Tests on Subsoils of Bangkok and Adjacent Areas, Appendix III, Volume 1.
AIT(1978), Subsurface Soil Characteristics of Bangkok and Adjacent Areas, Volume 1, 2.

Figure 7.3.8	e−logP CURVES OF CALYEY SOILS (DEPTH = 15.0m to 20.0m)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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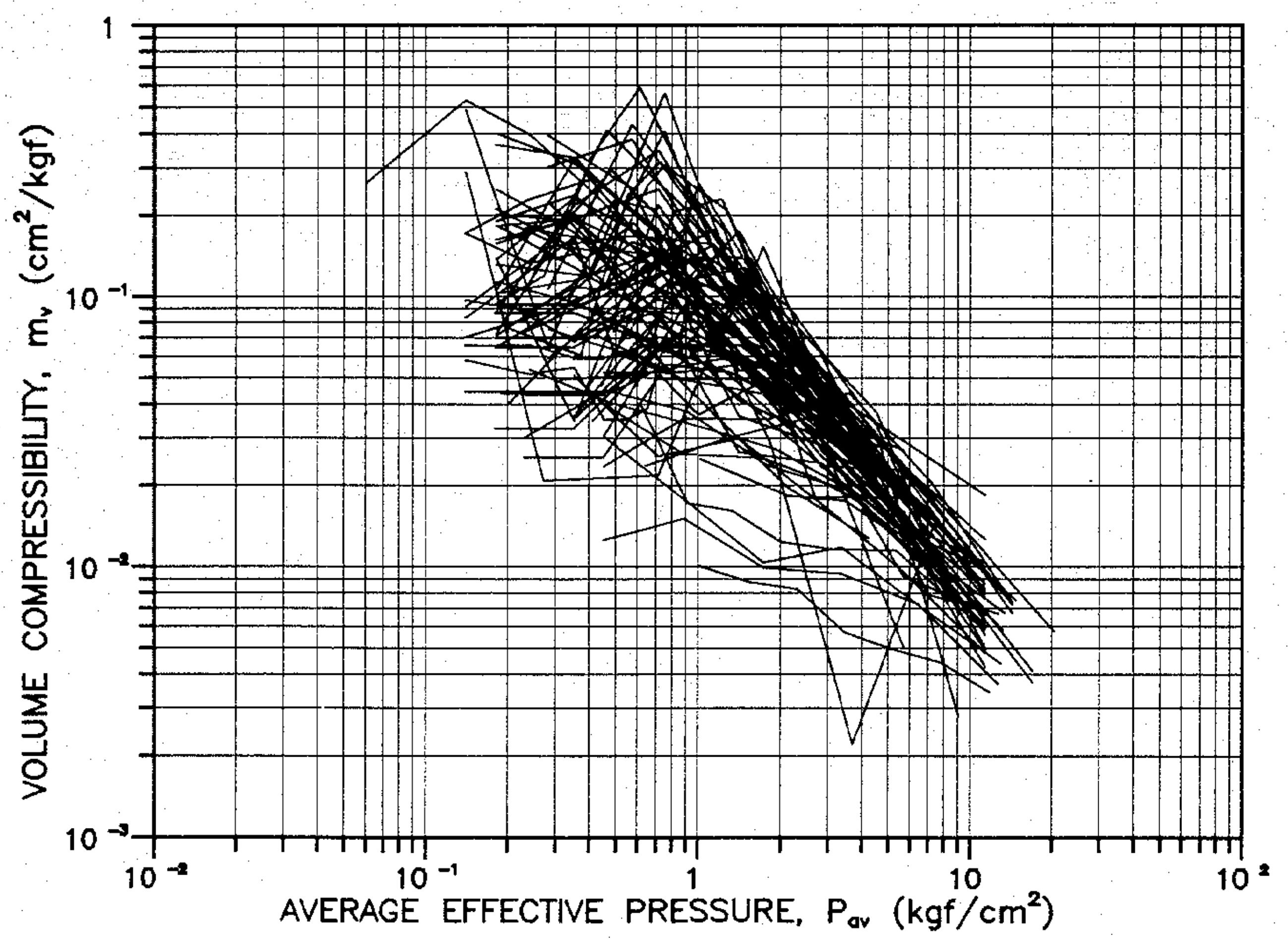

Data source: AIT(1978), Results of Laboratory Tests on Subsoils of Bangkok and Adjacent Areas, Appendix III, Volume 1.
AIT(1978), Subsurface Soil Characteristics of Bangkok and Adjacent Areas, Volume 1, 2.

Figure 7.3.9 $\log m_v - \log P_{av}$ CURVES OF CALYEY SOILS (DEPTH = 0.0m to 5.0m)

THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY

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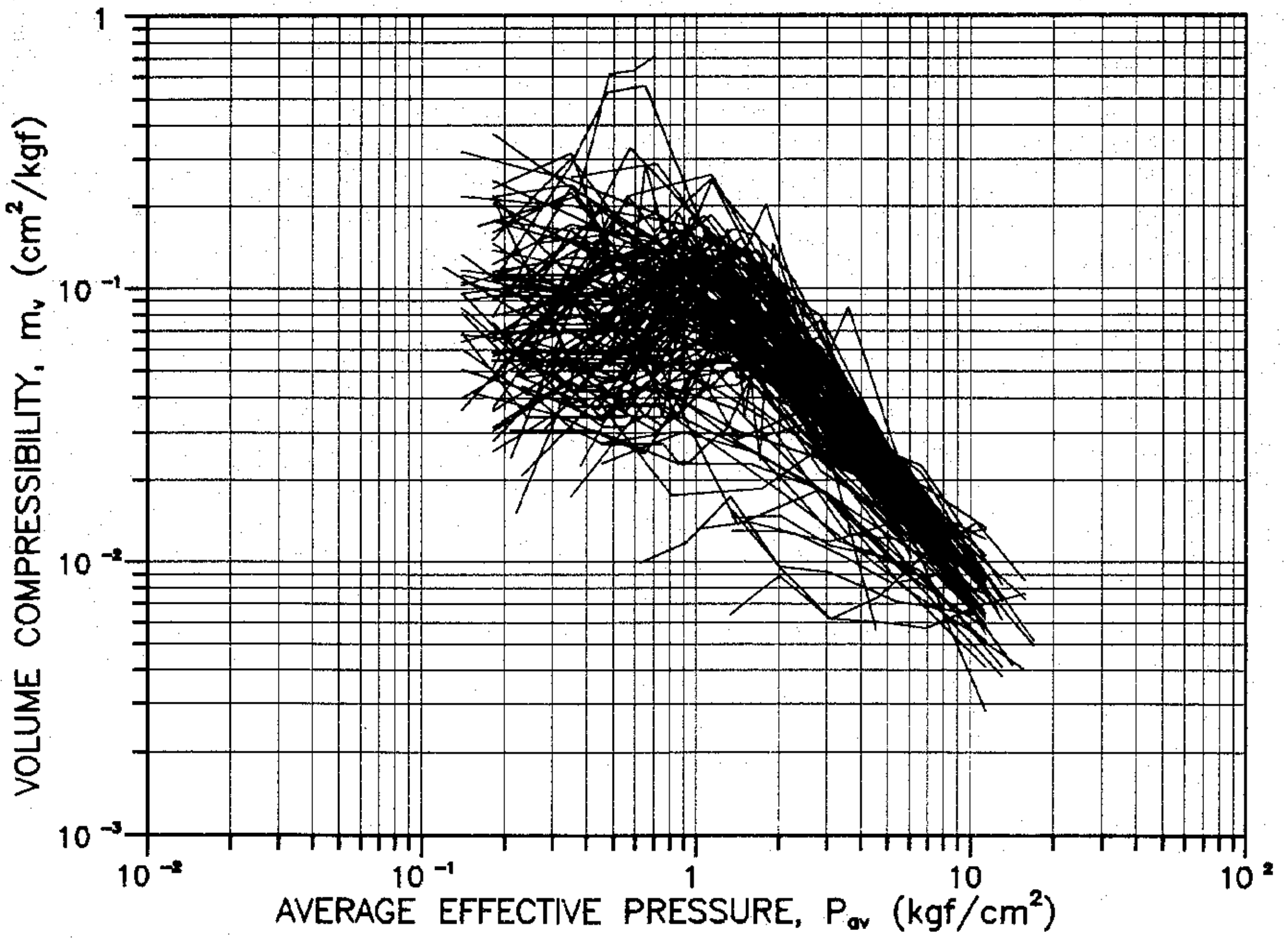

Data source: AIT(1978), Results of Laboratory Tests on Subsoils of Bangkok and Adjacent Areas, Appendix III, Volume 1.
AIT(1978), Subsurface Soil Characteristics of Bangkok and Adjacent Areas, Volume 1, 2.

Figure 7.3.10	$\log m_v - \log P_{av}$ CURVES OF CALYEY SOILS (DEPTH = 5.0m to 10.0m)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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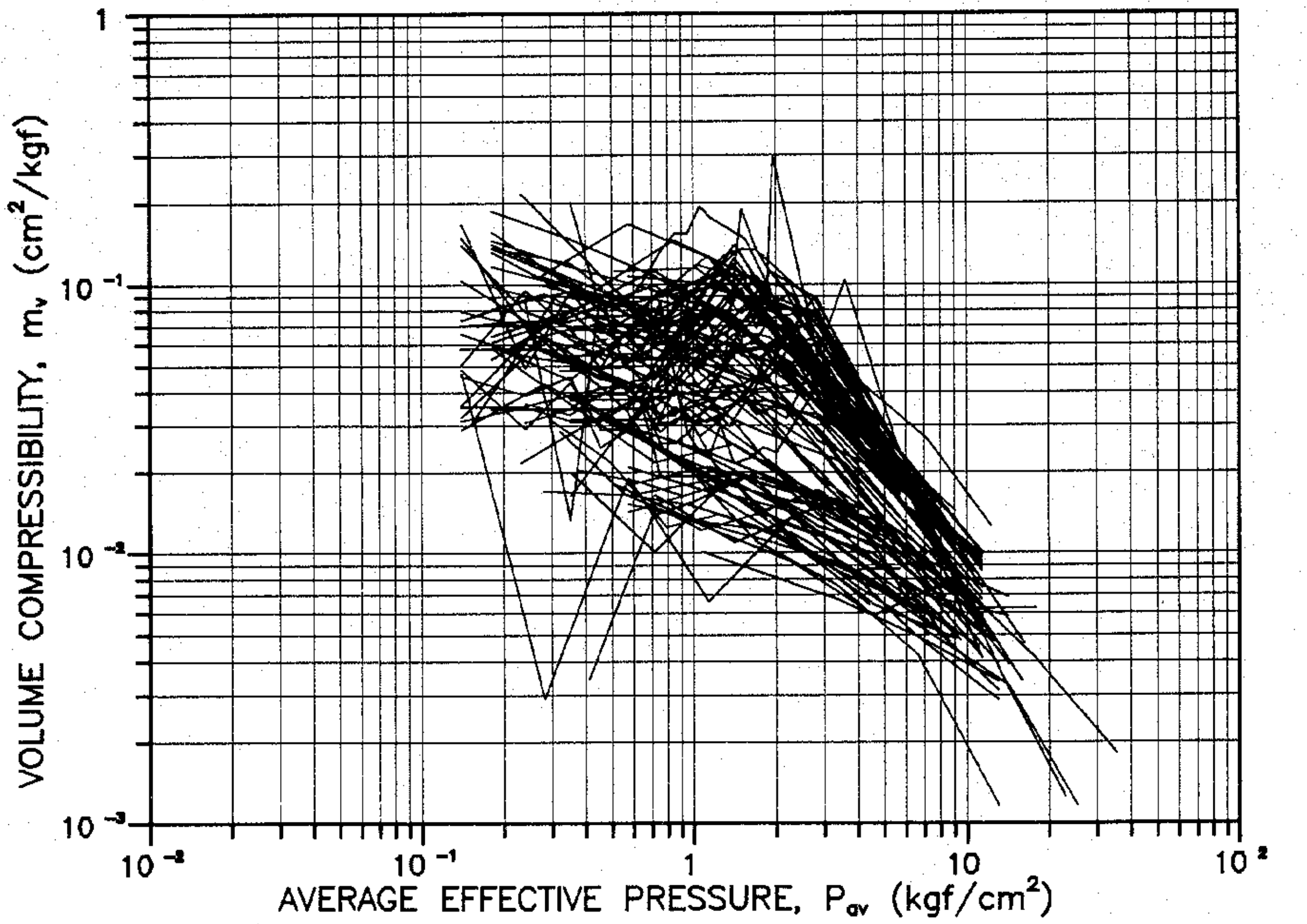

Data source: AIT(1978), Results of Laboratory Tests on Subsoils of Bangkok and Adjacent Areas, Appendix III, Volume 1.
AIT(1978), Subsurface Soil Characteristics of Bangkok and Adjacent Areas, Volume 1, 2.

Figure 7.3.11	$\log m_v - \log P_{av}$ CURVES OF CALYEY SOILS (DEPTH = 10.0m to 15.0m)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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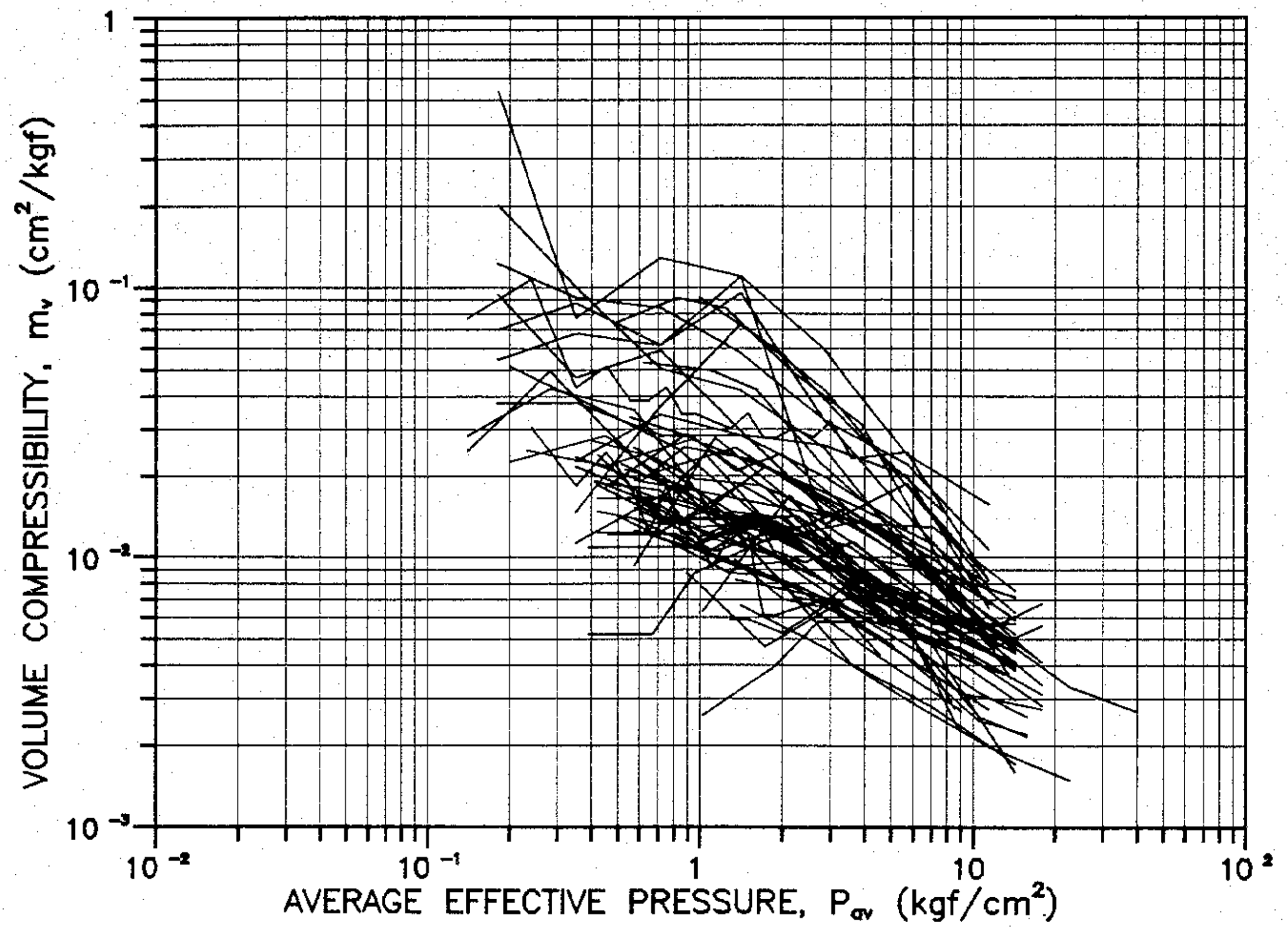

Data source: AIT(1978), Results of Laboratory Tests on Subsoils of Bangkok and Adjacent Areas, Appendix III, Volume 1.
AIT(1978), Subsurface Soil Characteristics of Bangkok and Adjacent Areas, Volume 1, 2.

Figure 7.3.12 logm$_v$–logP$_{av}$ CURVES OF CALYEY SOILS (DEPTH = 15.0m to 20.0m)

THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY

JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)

KOKUSAI KOGYO CO., LTD.

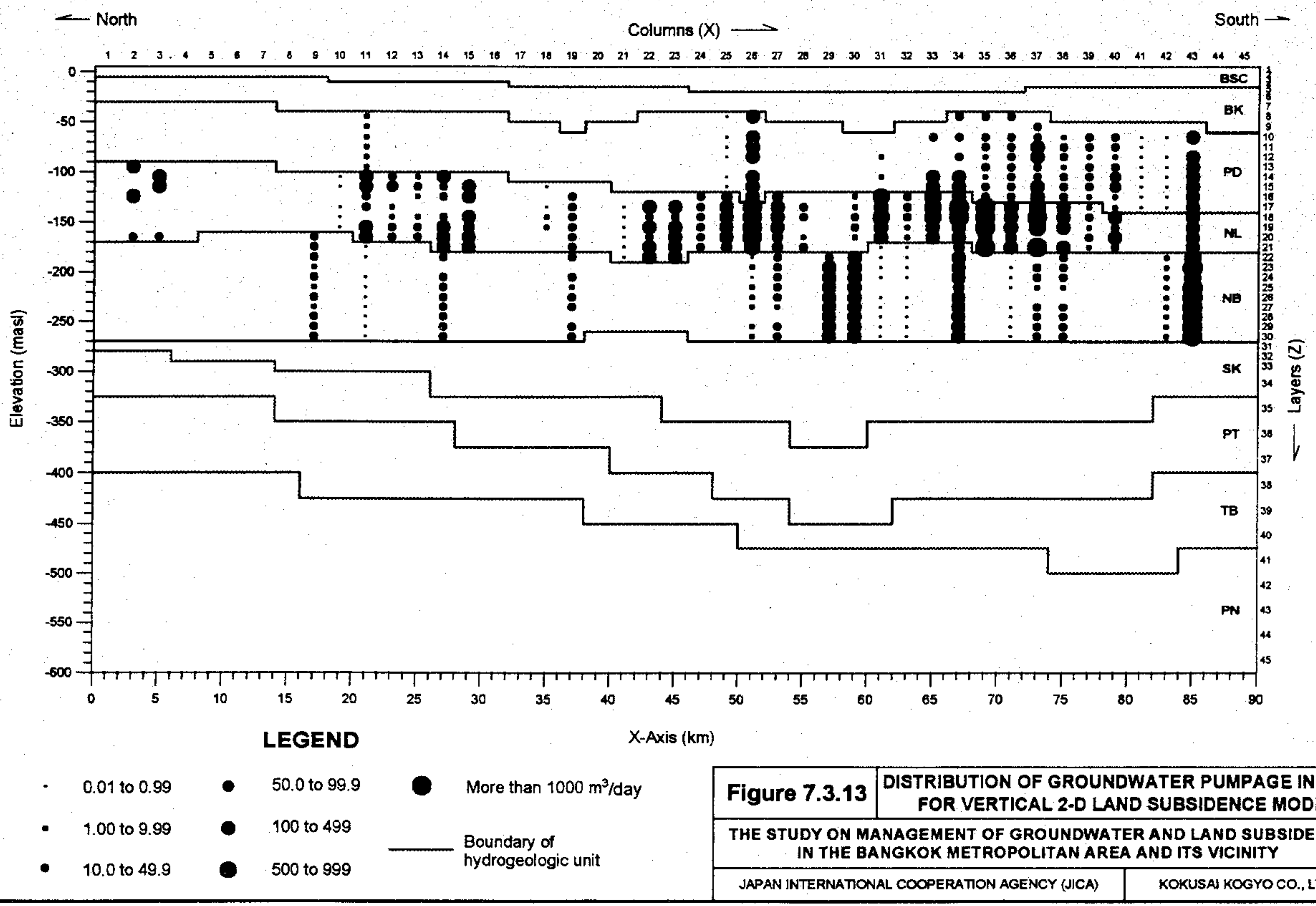

Figure 7.3.13	**DISTRIBUTION OF GROUNDWATER PUMPAGE IN 1992 FOR VERTICAL 2-D LAND SUBSIDENCE MODEL**
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

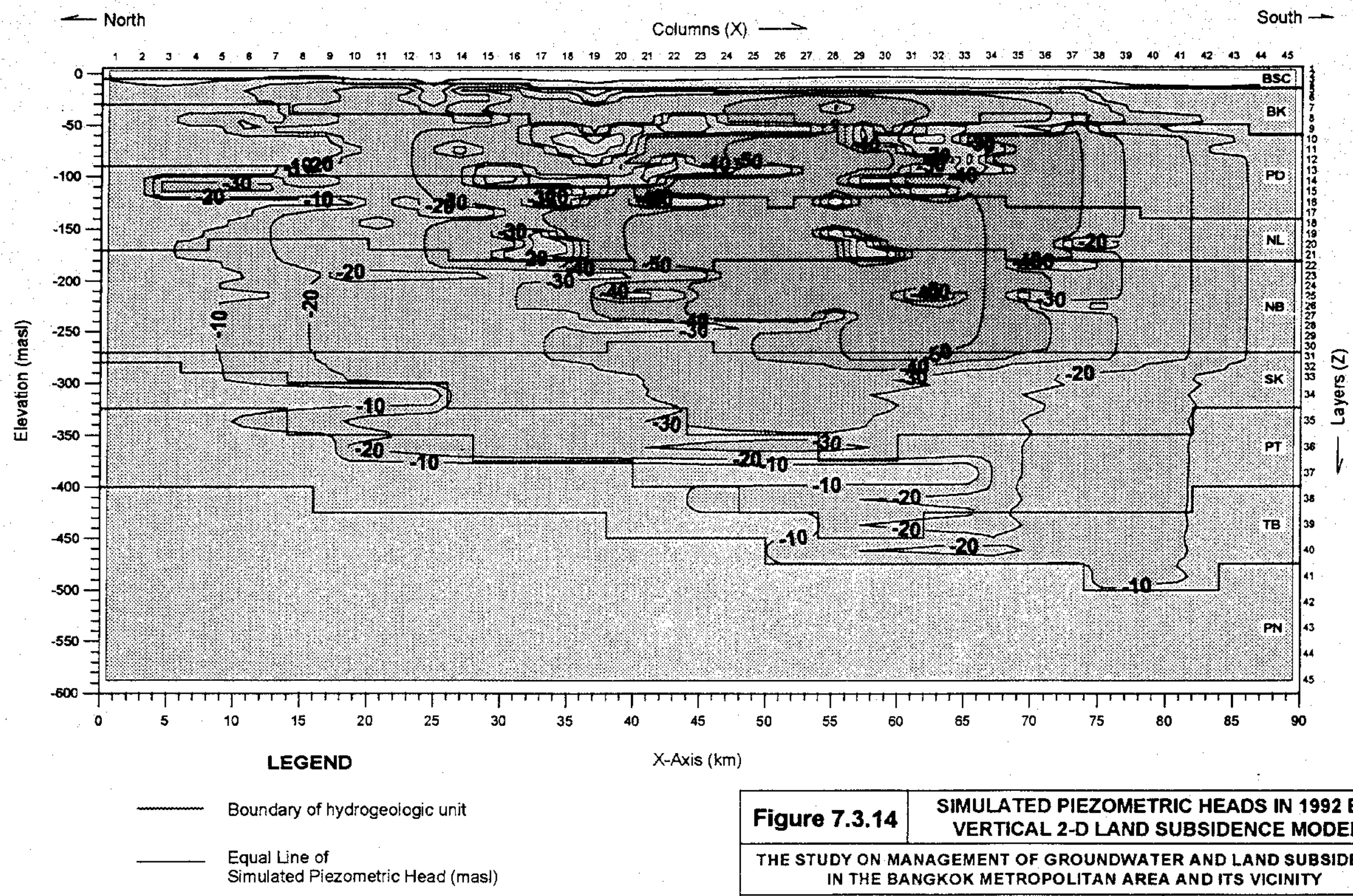

Figure 7.3.14	**SIMULATED PIEZOMETRIC HEADS IN 1992 BY VERTICAL 2-D LAND SUBSIDENCE MODEL**

THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY

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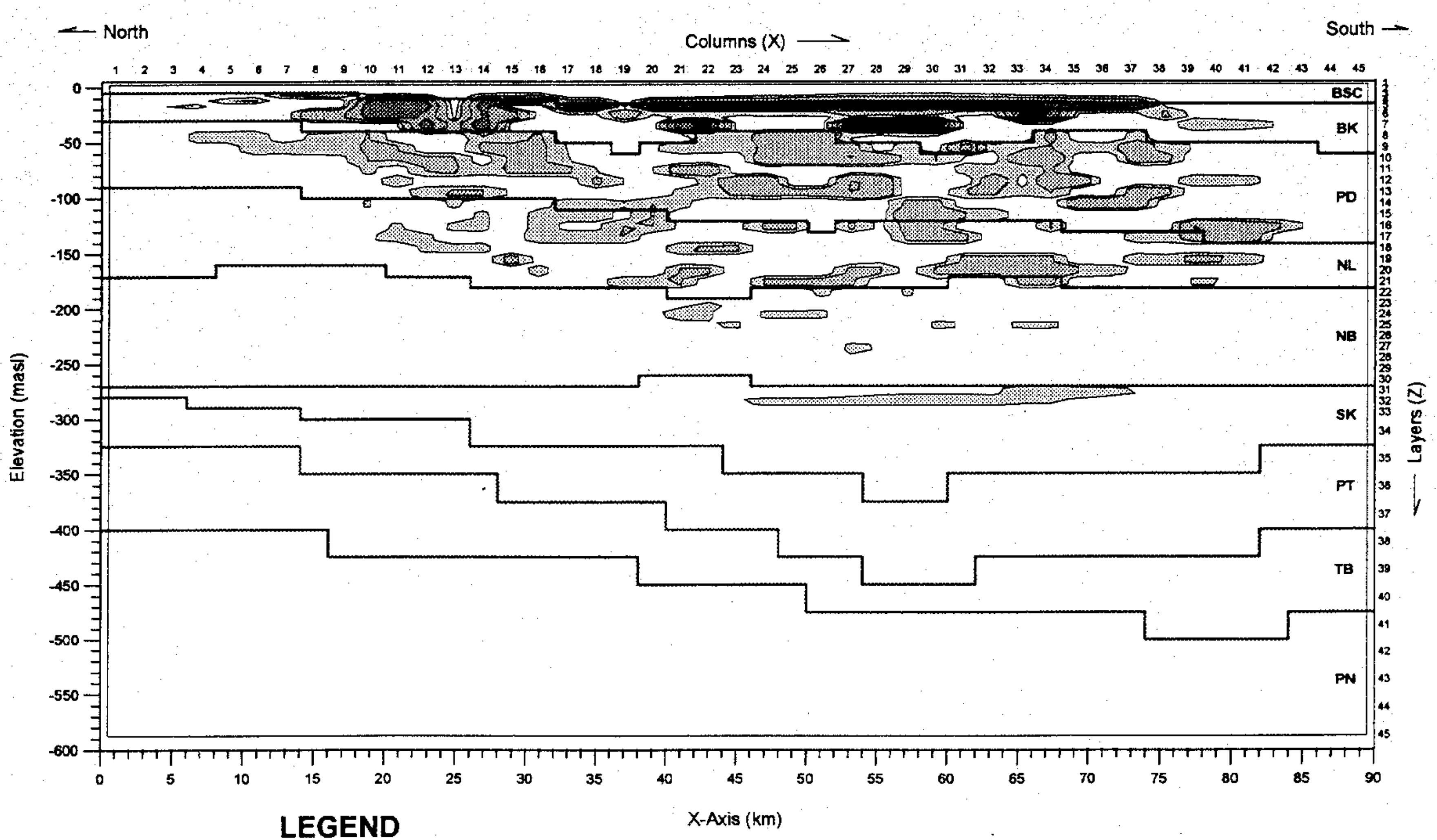

LEGEND

SIMULATED COMPRESSION (cm/m)

■	▩	▨	▨	░	□
-1.0	-0.8	-0.6	-0.4	-0.2	-0.1

Figure 7.3.15 SIMULATED COMPRESSION FROM 1983 TO 1992 BY VERTICAL 2-D LAND SUBSIDENCE MODEL

THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY

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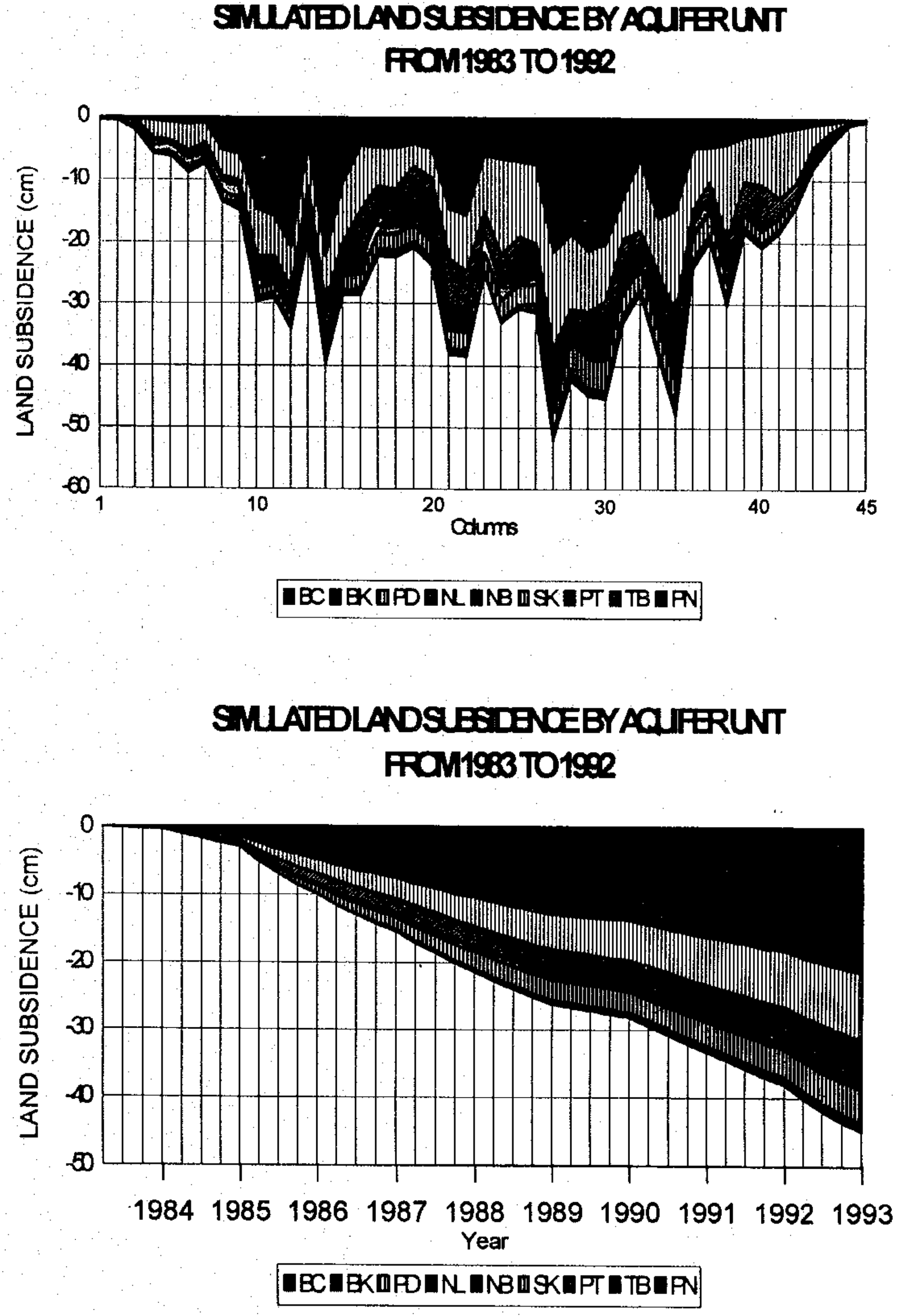

Figure 7.3.16 RESULTS OF LAND SUBSIDENCE SIMULATION BY VERTICAL 2-D MODEL

THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY

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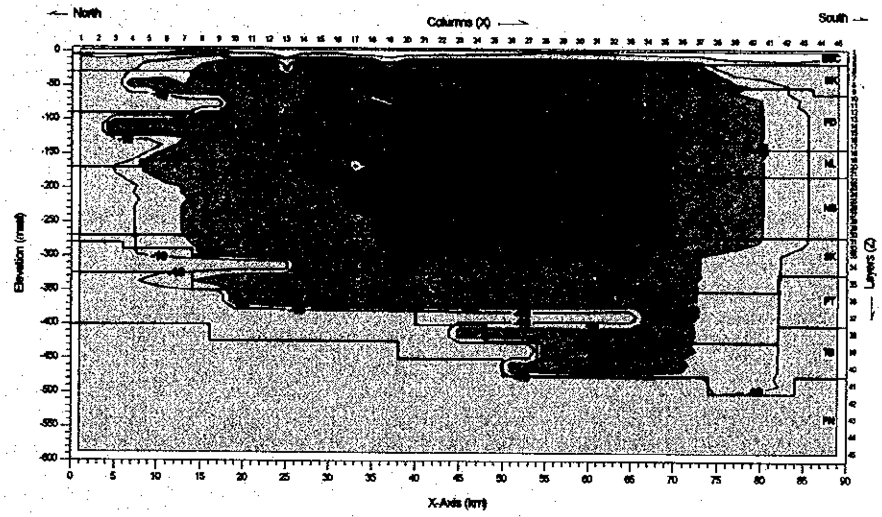
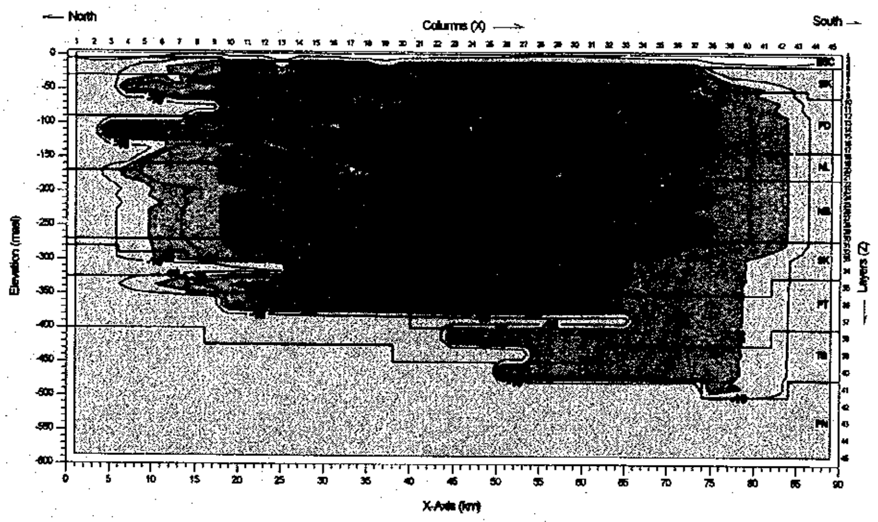
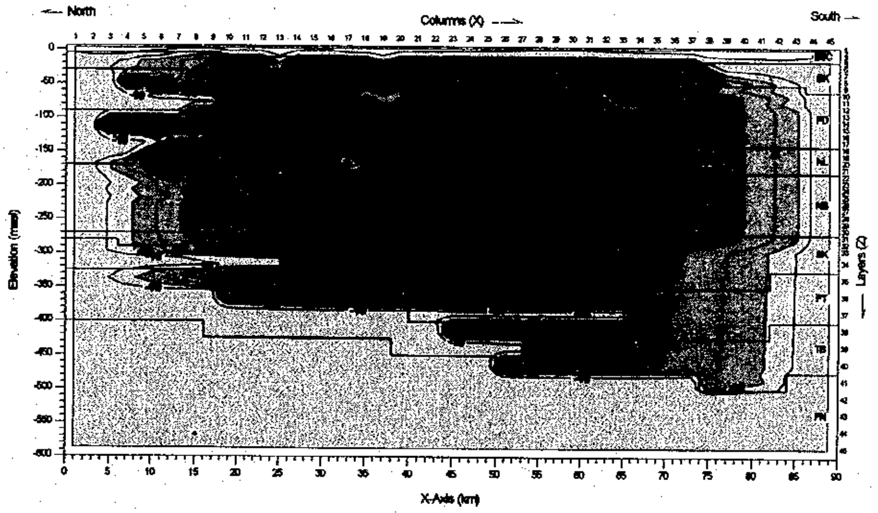


(a) 1997



(b) 2007



(c) 2017

LEGEND

Boundary of hydrogeologic unit

Equal Line of Simulated Piezometric Head (masl)

Figure 7.3.17

SIMULATED PIEZOMETRIC HEADS
BY SCENARIO 1

THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY

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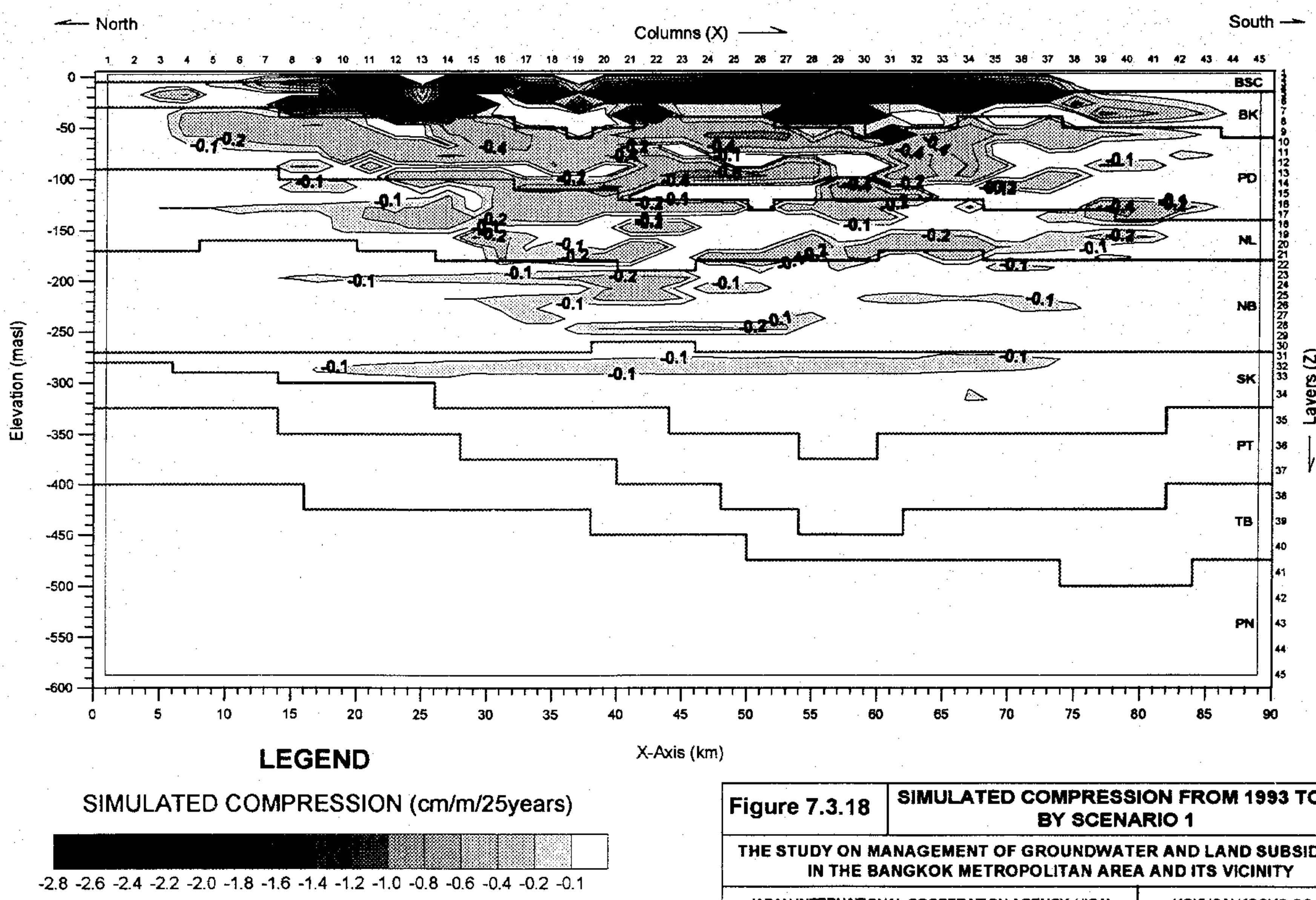

Figure 7.3.18	SIMULATED COMPRESSION FROM 1993 TO 2017 BY SCENARIO 1

THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY

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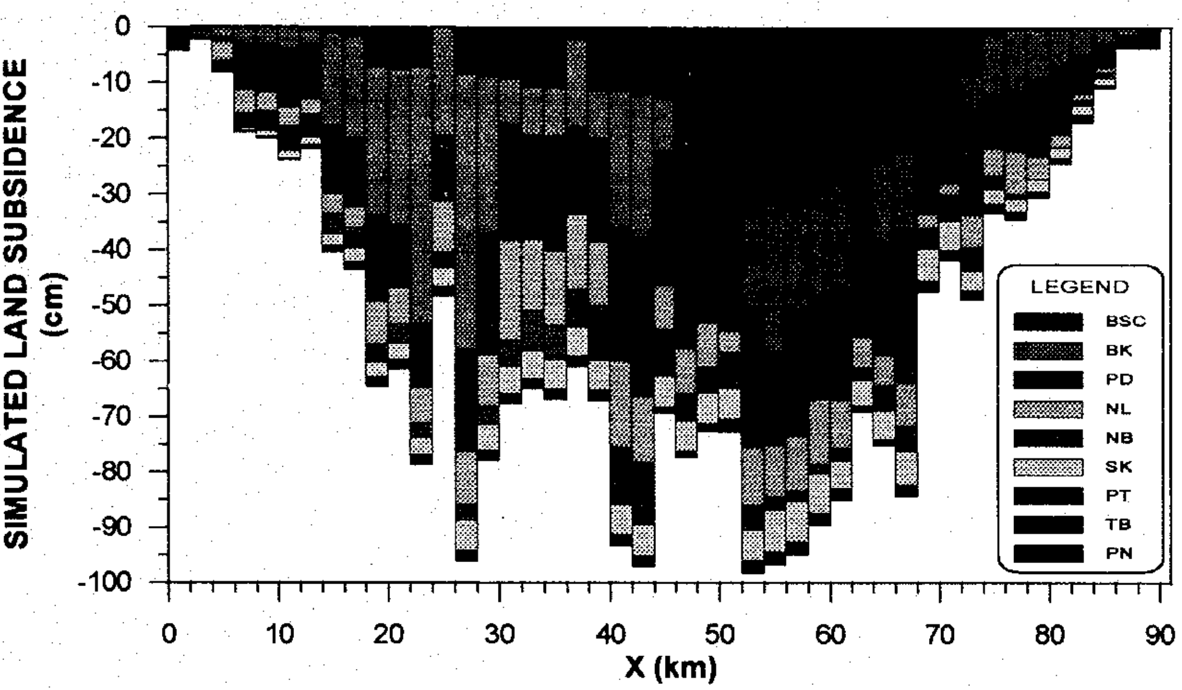
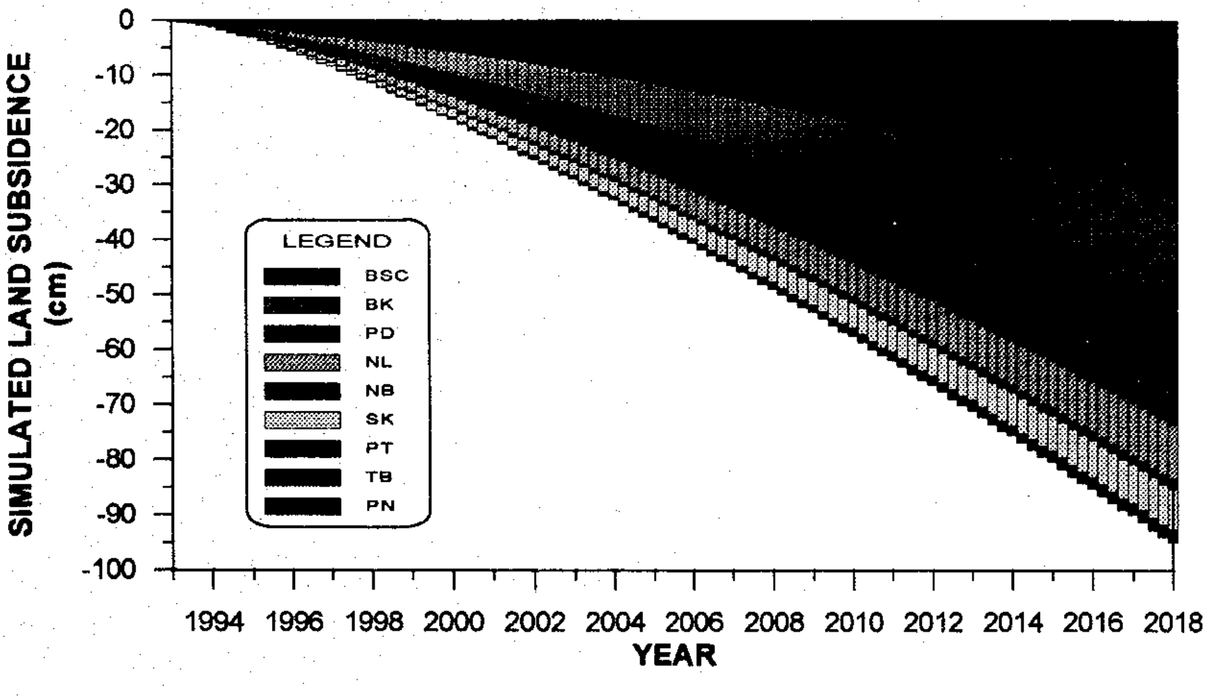
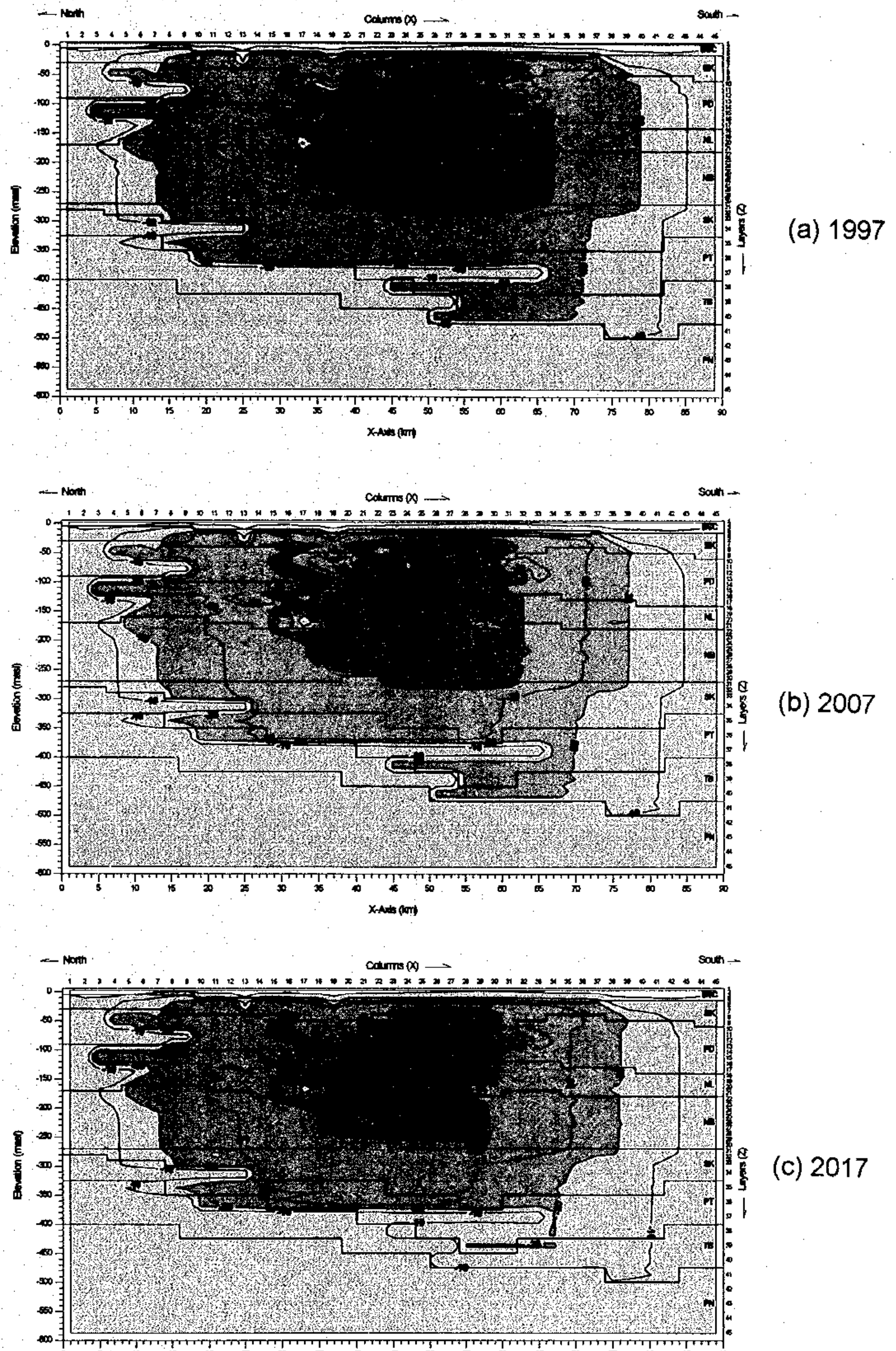


(a) Simulated Land Subsidence from 1993 to 2017 along the model line



(b) Simulated Land Subsidence at Site-A

Figure 7.3.19	SIMULATED LAND SUBSIDENCE BY SCENARIO 1
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



LEGEND

——— Boundary of hydrogeologic unit

- - - Equal Line of Simulated Piezometric Head (masl)

Figure 7.3.20	SIMULATED PIEZOMETRIC HEADS BY SCENARIO 7

THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY

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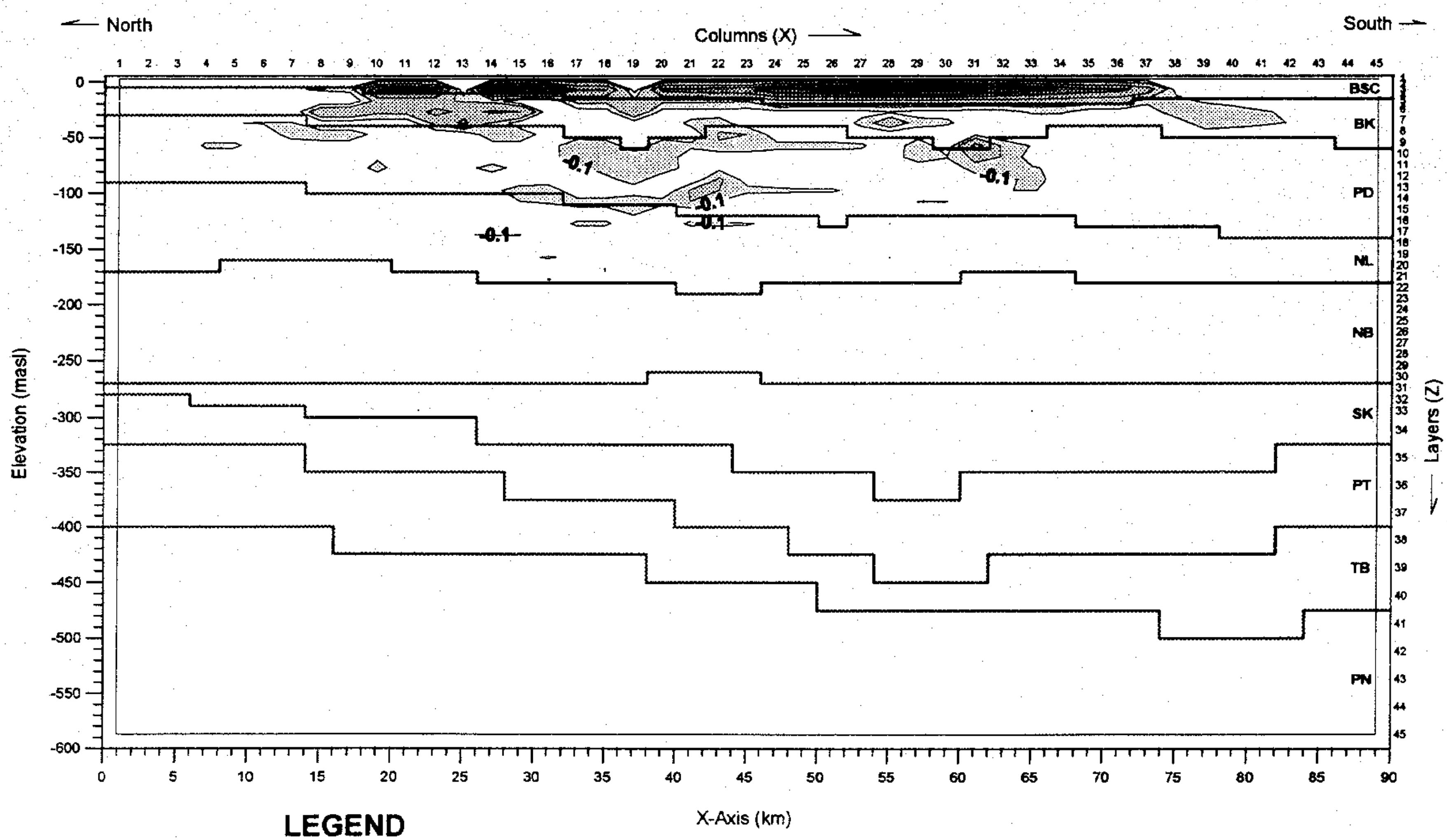

LEGEND

SIMULATED COMPRESSION (cm/m/25years)

-2.8 -2.6 -2.4 -2.2 -2.0 -1.8 -1.6 -1.4 -1.2 -1.0 -0.8 -0.6 -0.4 -0.2 -0.1

Figure 7.3.21	SIMULATED COMPRESSION FROM 1993 TO 2017 BY SCENARIO 7

THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY

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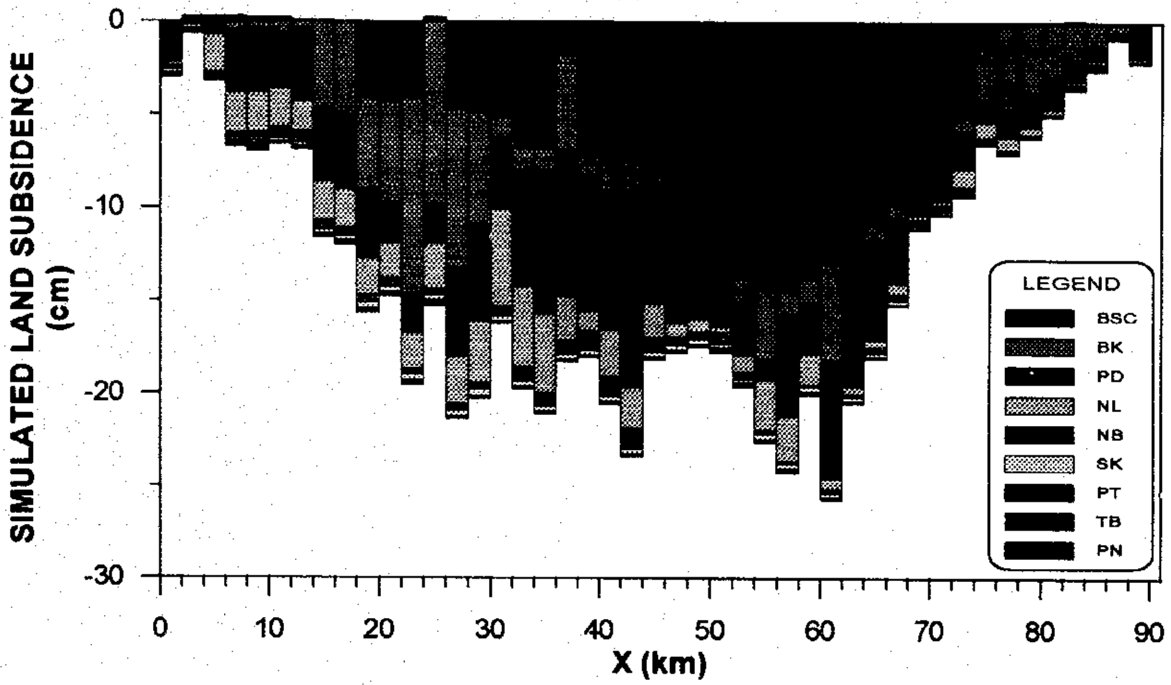
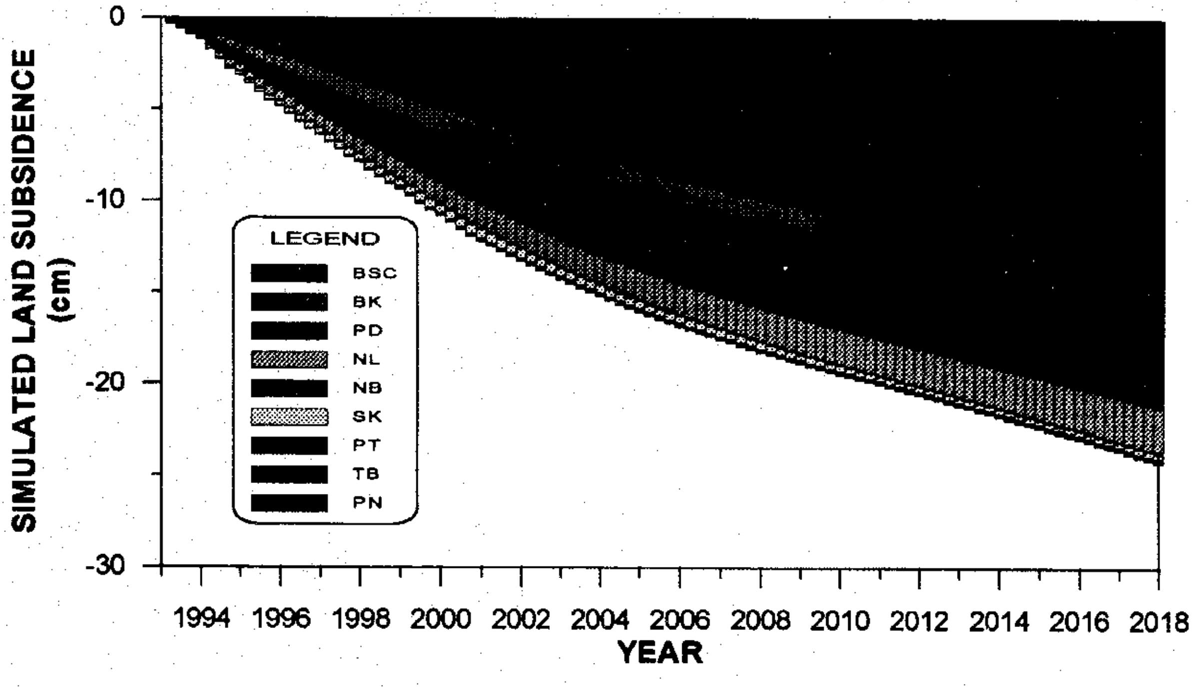


(a) Simulated Land Subsidence from 1993 to 2017 along the model line



(b) Simulated Land Subsidence at Site-A

Figure 7.3.22	SIMULATED LAND SUBSIDENCE BY SCENARIO 7
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

7.4 Vertical 2-D Solute Transport Model

7.4.1 Model Concept

The vertical two-dimensional solute transport model was applied to the Study Area. The model can simulate vertical groundwater flow as well as vertical movement of saline water. Merits of using the vertical two-dimensional model are:

- to reflect complicated hydrogeologic structures to the model
- to simulate vertical distribution of piezometric heads in detail
- to understand mechanism of saline water intrusion

The vertical 2-D model considers the groundwater flow system in x-axis and z-axis, where x-axis indicates horizontal direction and z-axis indicates vertical direction. The vertical 2-D groundwater flow model neglects the flow perpendicular to the x-z plane. Therefore, it is a good idea to select a model line located perpendicular to the contour lines of piezometric levels.

The MOCDENSE program and MT3D program were used in the Study. MOCDENSE can simulate variable density fluids in which the concentration of the solute of interest affects the density of the fluids. MT3D can simulate advection, dispersion, and chemical reactions of contaminants in groundwater flow system in either two or three dimensions.

MOCDENSE was developed by W. E. Sanford and L. F. Konikow to simulate the flow in a cross-sectional plane rather than in an areal plane. Because the problem of interest involves variable density, the model solves for fluid pressure rather than piezometric head in the flow equation; the solution to the flow equation is still obtained using a finite difference method. Solute transport is simulated with the method of characteristics. Density is considered to be a function of the concentration of one of the constituents.

MT3D was originally developed by C. Zheng (1990). The program uses a mixed Eulerian-Lagrangian approach to the solution of the advective-dispersive-reactive equation, based on a combination of the method of characteristics and the modified method of characteristics. MT3D can simulate the flow of groundwater that has a constant and uniform fluid density. The MT3D program was developed for use with any block-centered finite difference flow model such as MODFLOW. Now the PM program (version 3.0) can be used to prepare input data for MT3D.

MOCDENSE and MT3D use the method of characteristics, which has been widely used in field studies. The method of characteristics uses a conventional particle tracking technique for solving the advection term. At the beginning of the simulation, a set of moving particles is distributed in the flow field either randomly or with a fixed pattern. A concentration and a position in the Cartesian coordinate system are associated with each of these particles. Particles are tracked forward through the flow fields using a small time increment. At the end of each time increment, the average concentration at cell due to advection alone over the time increment is evaluated from the concentrations of moving particles which happen to be located within the cell.

7.4.2 Flow Equation of Variable Density Fluid

The MOCDENSE program solves an equation which represents the flow of a compressible fluid through a heterogeneous and anisotropic confined aquifer. The general flow equation can be expressed in Cartesian tensor notation as:

$$\frac{\partial}{\partial x_i}\left[\frac{\rho g k_{ij}}{\mu}\left(\frac{\partial P}{\partial x_i} + \rho g\frac{\partial z}{\partial x_j}\right)\right] = Ss\cdot\frac{\partial P}{\partial t} + W\rho{*}g \qquad (7.4.1)$$

where

K_{ij} is the intrinsic permeability (a second order tensor) (L^2);
ρ is the fluid density (ML^{-3});
μ is the dynamic viscosity ($ML^{-1}T^{-1}$);
P is the fluid pressure ($ML^{-1}T^{-2}$);
g is the gravitational acceleration constant (LT^{-2});
z is the elevation of the reference point above a standard datum (L);
Ss is the specific storage of the aquifer (L^{-1});
W is a source/sink volume flux per unit volume (T^{-1});
ρ^* is the density of the source/sink fluid (ML^{-3});
x_i are the Cartesian coordinates (L); and
t is time (T).

From this equation, hydraulic conductivity and piezometric head should be converted into intrinsic permeability and fluid pressure, respectively.

7.4.3 Solute Transport Equation

The MOCDENSE and MT3D use the solute transport equation, that is written as:

$$\frac{\partial C_n}{\partial t} = \frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C_n}{\partial x_j}\right) - \frac{\partial}{\partial x_j}(C_n V_i) - \frac{C'_n W}{\varepsilon} \qquad (7.4.2)$$

where

D_{ij} is the coefficient of hydrodynamic dispersion (a second order tensor) (L^2T^{-1});
V_i is the seepage velocity in the direction of x_i (LT^{-1});
C_n is the concentration of the nth constituent (ML^{-3});
C'_n is the concentration of the nth constituent in the source or sink fluid (ML^{-3}); and
ε is the effective porosity (dimensionless).

7.4.4 Required Input Data and Output Data

The required input data for the MOCDENSE are as follows:

<u>for simulation control</u>

- Maximum number of time steps in a pumping period

- Number of pumping period
- Maximum number of particles
- Initial number of particles per node
- Maximum number of cells that can be void of particles before particles are redistributed
- Number of constituents present
- Pumping period in years
- Convergence criteria in SIP
- Concentration change increment for density-dependent constituent to determine whether pressures are recalculated

for model grid

- Number of nodes in x-direction
- Number of nodes in z-direction
- Width of finite difference cell in x-direction
- Width in finite difference cell in z-direction
- Width (third dimension) of the aquifer cross-section

for hydrogeologic parameters

- Effective porosity
- Storage coefficient (set 0 for steady-state simulation)
- Longitudinal dispersivity
- Ratio of transverse to longitudinal dispersivity
- Ratio of K_{zz} to K_{xx}
- Molecular diffusion coefficient
- Intrinsic permeability
- Leakance coefficient
- Boundary codes
- Initial fluid pressure
- Initial concentration of the density-controlling constituent

The output data from MOCDENSE are computed fluid pressure, computed concentration, etc. These out put data are available at each time step.

The input data for MT3D can be prepared from the PM programs. Therefore, input parameters for simulation control, model grid, aquifer properties, optional packages, solver selection, and output control for the flow simulation are the same as the MODFLOW input. Followings are additional required data for MT3D from PM:

for simulation control

- Transport step size

for concentration

- Boundary indicator array for the concentration field
- Initial concentration
- Observation points

for optional packages

- Concentration of pumped water
- Concentration at constant head cells

for advection

- Advection solution method
- Courant number
- Maximum number of total moving particles allowed
- Particle tracking algorithm
- Concentration weighing factor
- Negligible relative concentration gradient
- Pattern for initial placement of particles
- Minimum and maximum numbers of particles allowed per cell
- Multiplier for the particle number at source cells

for dispersion

- Ratio of horizontal transverse dispersivity to longitudinal dispersivity
- Ratio of vertical transverse dispersivity to longitudinal dispersivity
- Effective molecular diffusion coefficient
- Longitudinal dispersivity

for chemical reaction

- Type of sorption

for output control

- output frequency

The output data from MT3D are as follows:

- Computed concentration
- Number of particles
- Retardation factor
- Dispersion coefficient

7.4.5 Model Assumptions

The MOCDENSE assumes that (1) flow is two-dimensional, with one of the principal axes being parallel to gravity, (2) constituents are conservative (nonreactive), and (3) density and viscosity are a function of concentration and not of other factors such as pressure and temperature.

The assumptions of MT3D for the flow simulation is the same as MODFLOW. For solute transport simulation, chemical reactions are assumed to be nonreactive, equilibrium-controlled linear or nonlinear sorption, and first order irreversible rate reactions.

7.4.6 Model Grid

The vertical 2-D solute transport model was constructed based on the hydrogeologic profile of N-3 prepared by the study team. The N-3 profile line is located from the DMR station No. 35 in north to station No. 10 in south (Figure 7.3.1). The profile was selected for the modeling because the line passes the area where saline water is found. According to the results of groundwater quality analysis by the Study Team, two (2) types of saline water were found along the profile line. Therefore, the model location was selected to simulate the movement of those types of saline water .

The grid width and length are fixed as 2km as shown in Figure 7.4.1. The total length of the model is 86km and the number of columns is 43. Then the vertical grid system was prepared as shown in Figure 7.4.2. A thickness of 10m is uniformly given to the cells from -10m to -400m in elevation, because the MOCDENSE program does not allow to change the thickness. There is also a limitation about numbers of columns and layers in the MOCDENSE so that the elevation only up to -400m was taken into account for the modeling.

The boundaries of hydrogeologic units and screens of the production wells located in the modeled area are also shown in Figure 7.4.2. The screen's data were retrieved from the database system. It is noted that the most production wells in Samut Prakan have screens set at Phra Pradaeng Aquifer and Bangkok Aquifer, while the screen depths become deeper with going to the north. The production wells in Pathum Thani extract groundwater from NB aquifer and SK aquifer.

7.4.7 Boundary Conditions

The entire cells of the model are active. The modeled grid is surrounded by no-flow boundaries to preclude the flow of water and dissolved chemicals across the boundaries. The constant pressure boundary is given to the top layer. The top cells and the right side of the model (Column No. = 43) were specified as constant concentration boundary for solute transport simulation.

7.4.8 Hydrogeologic Parameters

The hydrogeologic unit and facies labels, such as (clay), (sand + clay), (sand), (sand + gravel), were assigned to each cell as shown in Figure 7.4.3. Then the required hydrogeologic parameters were given to each cell.

(1) Top and bottom elevations
Because the vertical 2-D model considers the groundwater flow in a cross-sectional plane, the width of a cell becomes the layer thickness for the MODFLOW model. Therefore, 0 masl and -2,000 masl were assigned to the top elevation and the bottom elevation, respectively. Then, PM computes the thickness of model grids as 2,000m.

(2) Type of each layer
The aquifer type must be specified as confined aquifer.

(3) Porosity
The porosity value of 0.05 was uniformly given to the model.

(4) Specific storage

MT3D program requires specific storage for the flow simulation. Although the Block-Centered Flow (BCF) Package of MODFLOW program requires dimensionless storage coefficient values in each layer of the model, however, it is only needed to specify specific storage values for each cell in PM. Then PM converts the specific storage value into dimensionless storage coefficient by multiplying the layer thickness of the cell.

As mentioned in Section 7.3.8, the initial storage coefficient of (sand) cells and (sand + gravel) cells were assumed to be 1.0E-3, then this value was converted into specific storage by dividing the value by the thickness of the cell.

The specific storage values of (clay) cells and (sand + clay) cells were computed by equation (7.2.5) from the volume compressibility values obtained from consolidation tests.

(5) Storage coefficient

MOCDENSE requires storage coefficient value to identify whether the simulation is steady-state or transient. In the Study, MOCDENSE was only used to simulate initial concentration of groundwater so that a value of 0 was uniformly assigned.

(6) Hydraulic conductivity and intrinsic permeability

The MT3D uses hydraulic conductivity in model input. At first, the hydraulic conductivity values were prepared for the PM program. Then, after the calibration of piezometric heads, the calibrated hydraulic conductivity values were converted into intrinsic permeability.

The parameter of transmissivity is the most important parameter for the model. PM will compute transmissivity from horizontal hydraulic conductivity (or permeability) by multiplying the layer thickness. An anisotropy factor (*Tyy* / *Txx*) can be specified in the model.

As already mentioned in Section 7.2.8, transmissivity values of each aquifer unit were investigated by the production well's data. Then the logarithmic average value and the range of variation were examined by aquifer unit as shown in Figure 7.2.25. Based on the analysis, hydraulic conductivity values of (sand + clay) cells, (sand) cells, and (sand + gravel) cells were input by aquifer unit. For the initial input, the logarithmic value was given to (sand) cells. The values of (Avg. + STD) and (Avg. - STD) were given to (sand + gravel) cells and (sand + clay) cells, respectively.

The hydraulic conductivity values of (clay) cells were estimated from the permeability values obtained from the consolidation tests by equation (7.2.15). Based on Figure 7.2.56, logarithmic average values of clay permeability were input to the model.

For MOCDENSE input, the intrinsic permeability (physical permeability) must be specified instead of hydraulic conductivity, because the hydraulic conductivity values in the fresh water zone and saltwater zone would be different. The relation between hydraulic conductivity and intrinsic permeability is:

$$k = k_p \frac{\gamma_w g}{\mu} \qquad (7.4.3)$$

where, k is hydraulic conductivity (LT^{-1}), k_p is intrinsic permeability (L^2), γ_w is unit weight of water (ML^{-3}), g is gravity acceleration (LT^{-2}), and μ is dynamic viscosity of water ($ML^{-1}T^{-1}$).

(7) Initial piezometric head and initial fluid pressure

At first, initial piezometric heads were prepared for MT3D model. The heads at top cells were assumed to be the ground elevation at the locations. The top cell located in the Gulf of Thailand was set as 0 masl. The initial heads from the second layer to the bottom were assumed to be 0 masl.

For MOCDENSE, the initial piezometric levels were converted into fluid pressures. It is noted that the column at the right side of the model represents the sea so that the fluid pressure values by depth were computed by considering the density of sea water. The density of sea water having 35,000 mg/L in chloride concentration is 1.025 g/cm^3 so that the fluid pressure increases 1.025 kgf/cm^2 with increasing depth at an interval of 10 m.

(8) Initial concentration

Initial chloride concentration for MOCDENSE was prepared firstly. The average chloride concentration of sea water, which is 35,000 mg/L, was given to the right side of the model from top to bottom.

The initial concentration for MT3D was prepared based on the results of MOCDENSE simulation.

7.4.9 Model Calibration

(1) Preparation of pumpage data

The historical pumpage data of the Case-2 were used for the calibration. The method of data preparation is the same as mentioned in Section 7.3.9. For the model calibration, yearly pumpage data were prepared from 1983 to 1992. The cell by cell pumpage was recalculated after modifying hydraulic conductivity during the model calibration.

Figure 7.4.4 shows the distribution of groundwater pumpage in 1992. The wells become deeper as going toward north. BK and PD layers are the main aquifers in the southern portion of the modeled area. In the central part, the pumped cells are mainly located in NL and NB aquifers. In Pathum Thani, NB and SK layers are the main aquifers.

(2) Historical heads calibration

The piezometric heads calibration is still very important for the solute transport model, because the model computes changes in concentration based on the groundwater flow. The heads calibration was carried out using the MODFLOW program.

The historical calibration of 20 time steps was carried out using the yearly pumpage data from 1983 to 1992. The former 10 steps (1 time step = 3 years) are steady-state calculation using the pumpage data in 1983. The historical calibration is from 11th step to 20th step where the yearly pumpage data from 1983 to 1992 are inputted.

During the calibration, the values of hydraulic conductivity and the ratio of (vertical hydraulic conductivity) / (horizontal hydraulic conductivity) were mainly modified. The specific storage values were given by the same method mentioned in Section 7.3.9.

After several trials, the computed heads showed a good agreement with the actual heads without modifying specific storage. It was again understood that the hydraulic conductivity at clay cells affects the vertical distribution of piezometric heads.

Figure 7.4.5 shows the simulated piezometric heads in 1992. The depression of piezometric head is located at NB and SK aquifers in Pathum Thani, showing below -50 masl. The piezometric head of NL aquifer below -30 masl is distributed in Pathum Thani and Bangkok.

(3) Solute transport calibration
The process of sea water intrusion follows the Ghyben-Herzberg principle. At first, the distribution of chloride ion concentration in the steady-state conditions without pumpage was simulated by the MOCDENSE program, which can simulate two-dimensional density-dependent flow. In this simulation, the southern margin of the model grid (Column No. = 43) was assumed to be the Gulf of Thailand. From the top to the bottom of the grid, the Cl^- concentration and density of sea water, those are 35,000 mg/L and 1.025 g/cm3 respectively, were uniformly assigned. The top layer of the grids located in the marsh near the shore line (Column No. 40 to 42) was assumed to have 30,000 mg/L in Cl^- concentration. The concentration of 100 mg/L in Cl^- concentration was given to the rest of the model cells. The hydraulic conductivity values (L/T) identified from the historical heads calibration were converted into the values of intrinsic permeability (L^2). The initial piezometric heads were also converted into the initial fluid pressures considering the density of the saline water. The top layer and the southern column of the model is assigned as the constant boundary for the fluid pressure and the Cl^- concentration.

Figure 7.4.6 shows the simulated Cl^- concentration by the steady-state simulation. The tongue of salt water entering from the right can be simulated as similar to the Ghyben-Herzberg relation. The transition zone between fresh water and salt water is simulated wider because longitudinal dispersivity was assumed to be 30.48 m. The result shows that the isochlor line of 10,000 mg/L enters 14 km from the shore line in NL and NB aquifers. The line of 20,000 mg/L is located 9 km from the sea.

The MT3D program was used to simulate historical Cl^- concentration. The density flow cannot be simulated by MT3D, however, the actual groundwater flow system is highly disturbed by the pumpage so that it is assumed for using MT3D that the movement of saline water is mainly depending on the groundwater flow caused by the pumpage. The simulated Cl^- concentration by MOCDENSE shown in Figure 7.4.6 was used as the initial concentration for the simulation. Figure 7.4.7 shows the simulated Cl^- concentration in 1992 after the 20 time steps simulation. The saline water in NB and SK aquifers further moves toward north, however, the saline water in BK, PD, and NL aquifers does not move toward inland because the saline groundwater is extracted by the wells tapped at the aquifers. As a result, the actual occurrence of saline water in the inland area such as Nonthaburi and Pathum Thani cannot be explained by the model situation, which assumes that the origin of saline water is the sea water.

Therefore, following two (2) cases were prepared to simulate the occurrence of saline water in the inland area:

Case-1: Source of saline water is the Chao Phraya River Water
Case-2: Source of saline water is the Bangkok Soft Clay

Case-1 is based on the fact that the Chao Phraya River is a tidal river. The basis of Case-2 is that the salt content of Bangkok Soft Clay is high. According to the results of core analyses, the shallow soils up to a depth around 50 m have high chloride content. The results of microfossil analyses suggest Case-2 because the depositional environment of the Bangkok Soft Clay is estimated as the marginal sea environment. It was confirmed at the JICA monitoring stations that no fossil water occurs in the deeper portions.

For Case-1 simulation, constant Cl^- concentration values ranging from 2,000 mg/L to 10,000 mg/L were given to the top cells where the Chao Phraya River is located. The top cells at the Gulf of Thailand and the marsh near the shore line have the same Cl^- concentration values of the MOCDENSE simulation model. The initial Cl^- concentration from Layers No. 2 to 41 is given as 100 mg/L.

Figure 7.4.8 shows the simulated Cl^- concentration in 1992 by Case-1. The saline water mainly moves downward from top cells where the Chap Phraya River is located. The movement is controlled by the layer facies and groundwater flow, however, the occurrence of saline water is limited near the river course. The result of the Case-1 simulation cannot match the actual wide distribution of saline water in the inland area..

For Case-2 simulation, constant Cl^- concentration values ranging from 2,000 mg/L to 10,000 mg/L were given to the Bangkok Soft Clay layer. The top cells at the Gulf of Thailand and the marsh near the shore line have the same Cl^- concentration values of the MOCDENSE simulation model. The initial Cl^- concentration from BK layer to TB layer is given as 100 mg/L.

The simulated Cl^- concentration in 1992 is shown in Figure 7.4.9. The simulated distribution pattern of saline water in the inland area is similar to the actual saline water distribution. The affected area by saline water decreases with increasing depth. The saline water mainly moves downward following the groundwater flow direction, but controlled by the hydrogeologic structures and the screen locations of pumping wells.

It is concluded from the simulation results that there are two (2) sources of saline water in the Study Area. One is the sea water from the Gulf of Thailand, and another is from the Bangkok Soft Clay. The sea water intrusion occurs in the Study Area, but the affected area is limited within about 20 km from the shore line. The mechanism of saline water occurrence in the inland area can be explained by the simulation model, assuming that the saline water originates from the Bangkok Soft Clay. The results of the simulation show a good agreement with not only the actual distribution of saline water but also the difference in chemical composition of saline water between the inland area and the coastal area.

7.4.10 Predictions

(1) Future pumpage

The future pumpage data for the period from 1993 to 2017 by Scenario 1 and Scenario 7 were arranged for the model to predict future behavior of the model. The two (2) scenarios were selected to compare future piezometric heads and land subsidence for the worst scenario (Scenario 1) with those of the best scenario (Scenario 7). The quarterly pumpage were computed by using QGPC. The pumpage values were distributed to the model cells by the method mentioned in Section 7.4.9.

(2) Scenario 1

The simulated piezometric heads in 1997, 2007, and 2017 are shown in Figure 7.4.10. The piezometric heads become deeper year by year. In 1997, the piezometric heads below -80 masl are distributed in NB and SK layers at Sam Khok, Pathum Thani. After 10 years, the piezometric heads from NB to PN layers range from -100 masl to -120 masl at Sam Khok area. The simulated piezometric heads in 2017 show below -160 masl near Sam Khok and the areas having below -60 masl in piezometric head are located in Bangkok, Nonthaburi, and Pathum Thani. The center of the depression is located in NB and SK layers, however, the piezometric heads in NL layer also decline below -80 masl in Nonthaburi and Bangkok.

The simulated chloride concentration in 1997, 2007, and 2017 is shown in Figure 7.4.11. Saline water having more than 1,000 mg/L in Cl^- concentration will intrude from BK to NL layers, then it will reach SK layer in some part of Pathum Thani by 1997. By the year 2007, NB layer will be totally contaminated by the saline water from Samut Prakan to southern part of Pathum Thani. SK layer from Bangkok to southern Pathum Thani will be totally contaminated by the saline water by 2017. Further, the saline water will intrude PT layer.

(3) Scenario 7

The simulated piezometric heads in 1997, 2007, and 2017 are shown in Figure 7.4.12. The piezometric heads will recover year by year. In 1997, the piezometric heads below -60 masl occurs in NB and SK layers at Sam Khok, Pathum Thani. After 10 years, the piezometric heads below -60 masl disappears and the heads below -50 masl are distributed in NB and SK layers. In 2017, the area below -50 masl in piezometric heads is limited in NB and SK layers at Sam Khok and the areas having below -40 masl in piezometric head are located only in Nonthaburi and Pathum Thani.

Figure 7.4.13 shows the simulated chloride concentration in 1997, 2007, and 2017. The downward movement of saline water will be slower than that of Scenario 1. NB aquifer will be totally contaminated up to southern Pathum Thani by the year 2017, however, fresh water having less than 1,000 mg/L in Cl^- concentration will remain at SK aquifer in Nonthaburi.

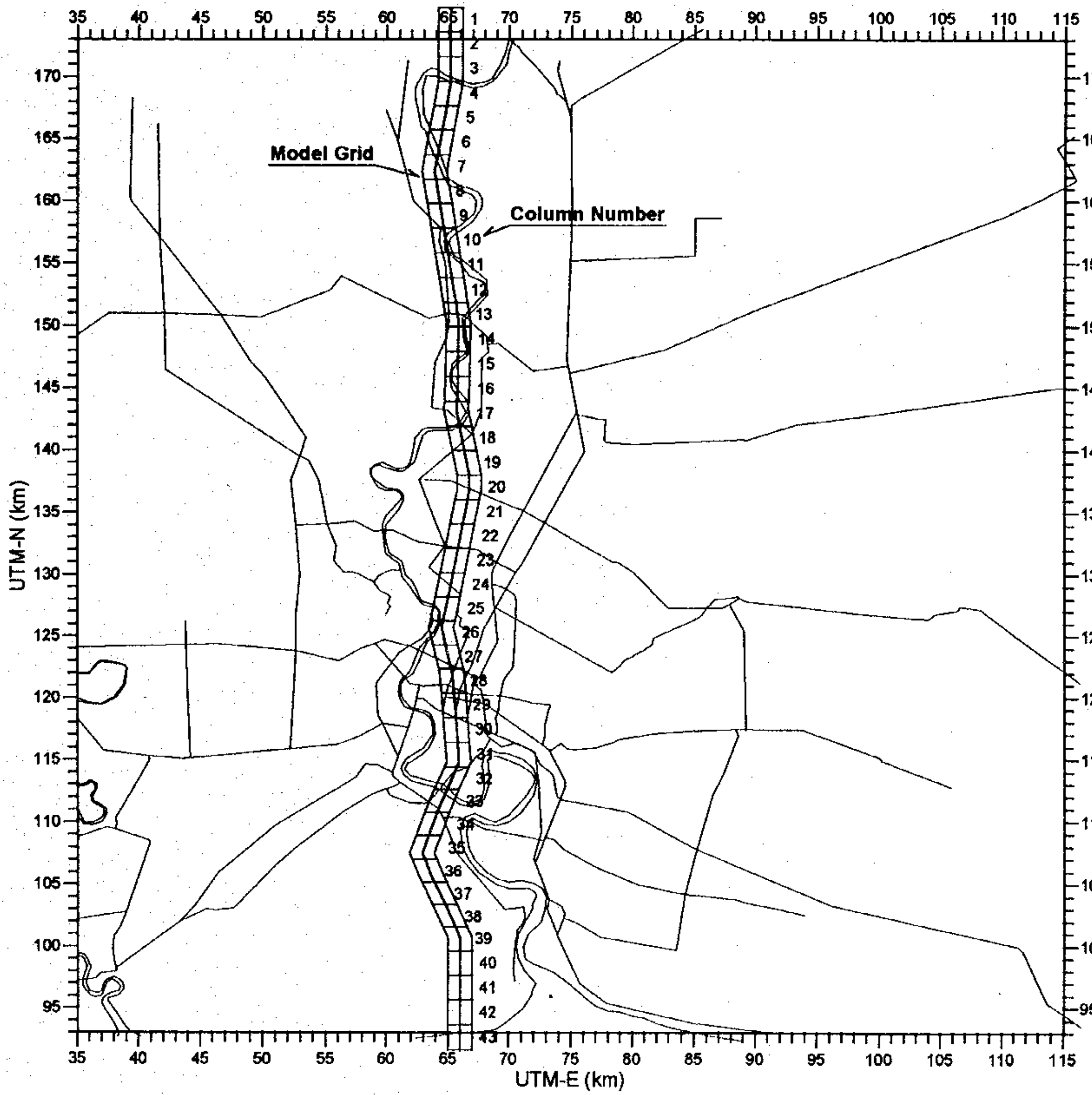


Figure 7.4.1 LOCATION OF VERTICAL 2-D SOLUTE TRANSPORT MODEL

THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY

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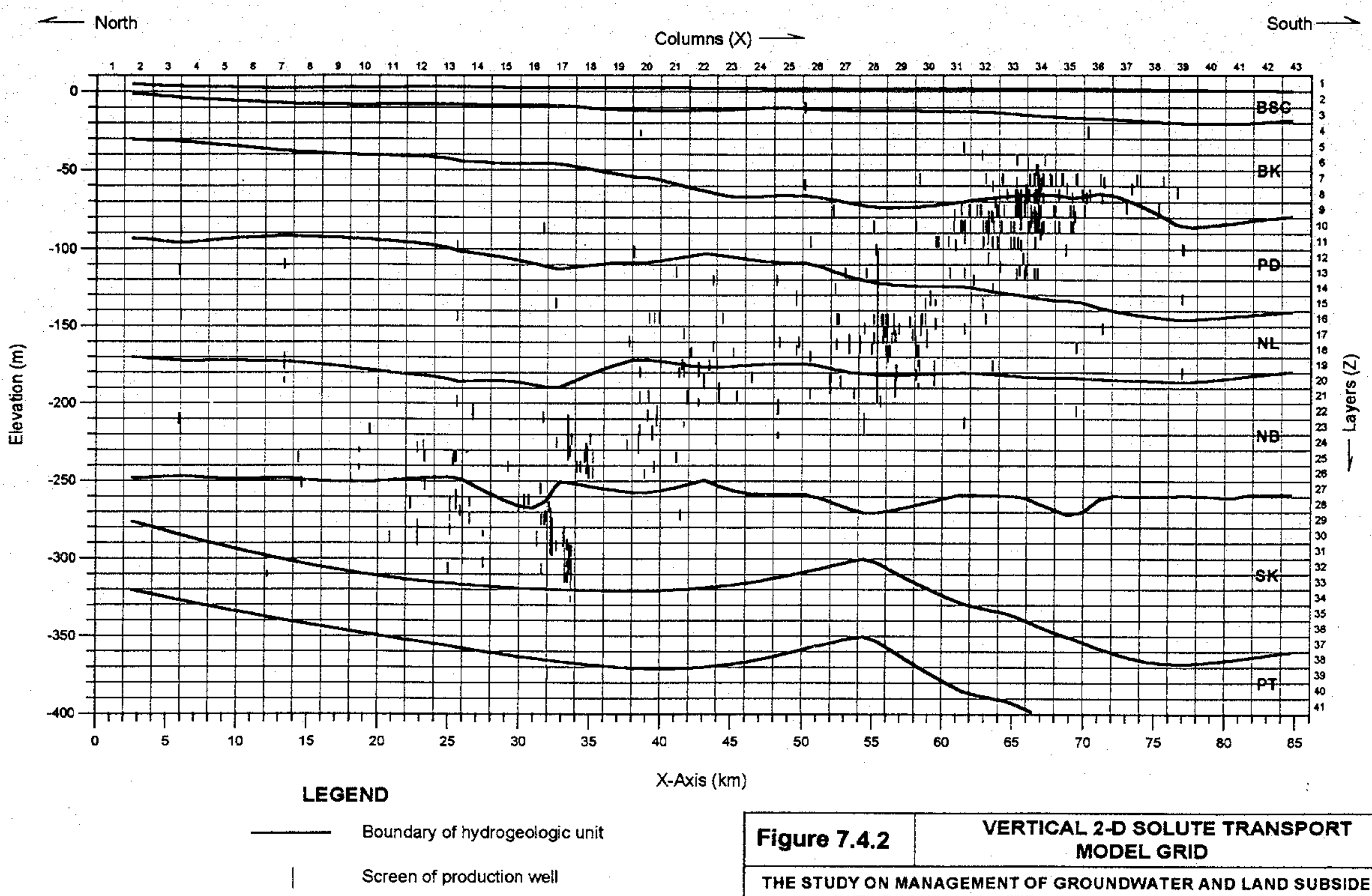

Figure 7.4.2 VERTICAL 2-D SOLUTE TRANSPORT MODEL GRID

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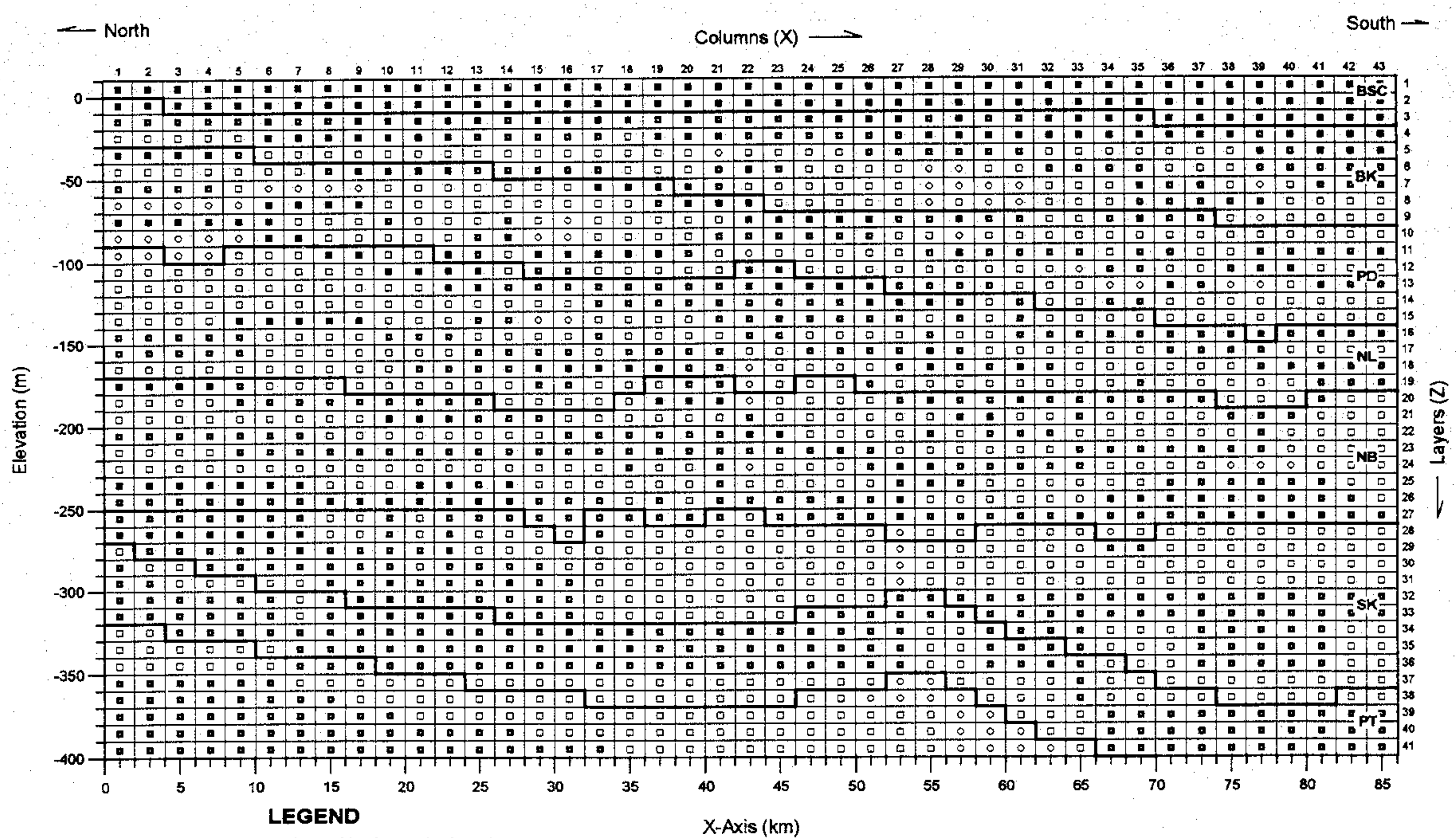

LEGEND

―― Boundary of hydrogeologic unit

■ Clay

▣ Sand + clay

□ Sand

◇ Sand + gravel

Figure 7.4.3 HYDROGEOLOGIC UNIT AND FACIES ALLOCATION FOR VERTICAL 2-D SOLUTE TRANSPORT MODEL

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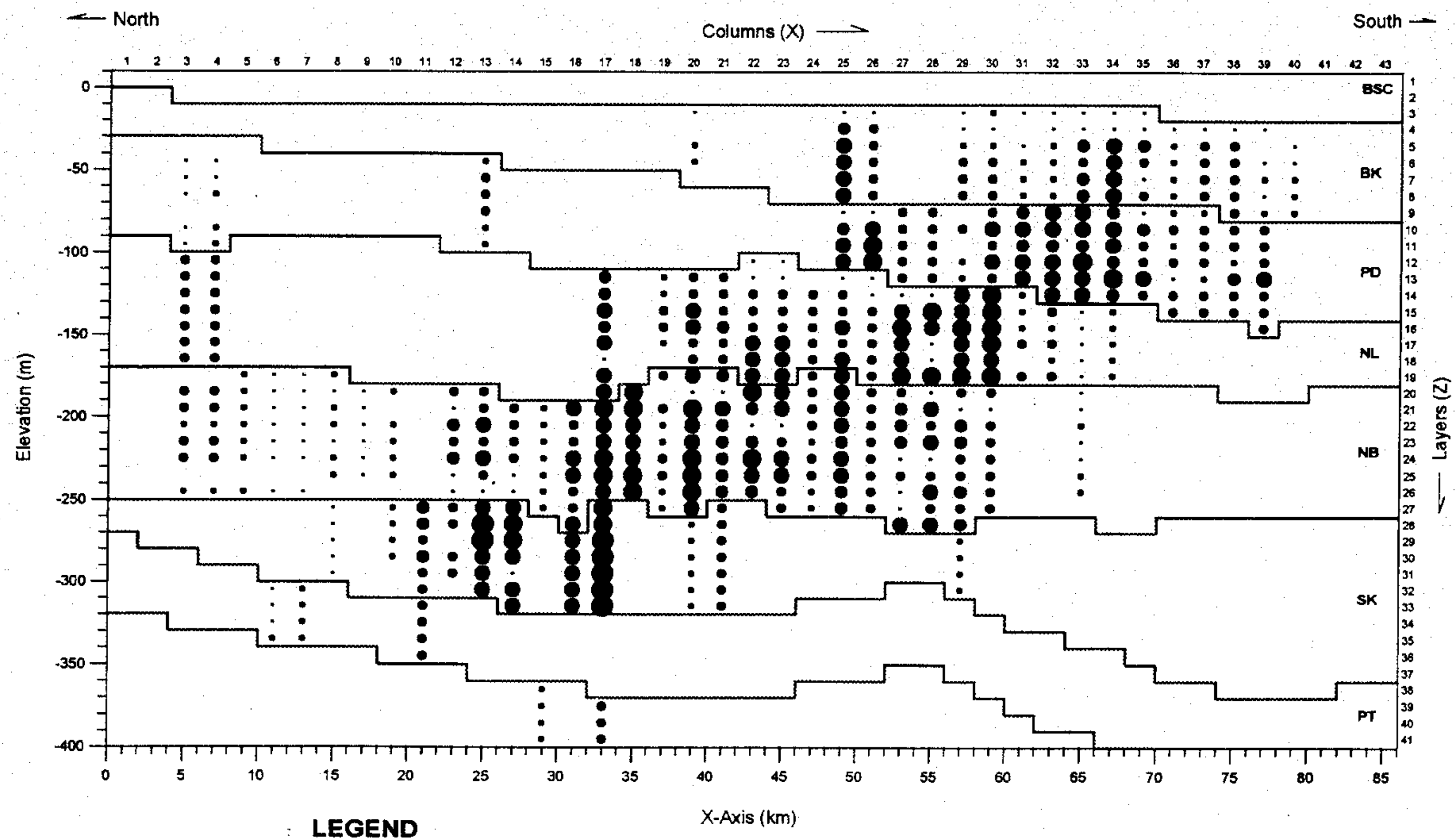

Figure 7.4.4	**DISTRIBUTION OF GROUNDWATER PUMPAGE IN 1992 FOR VERTICAL 2-D SOLUTE TRANSPORT MODEL**

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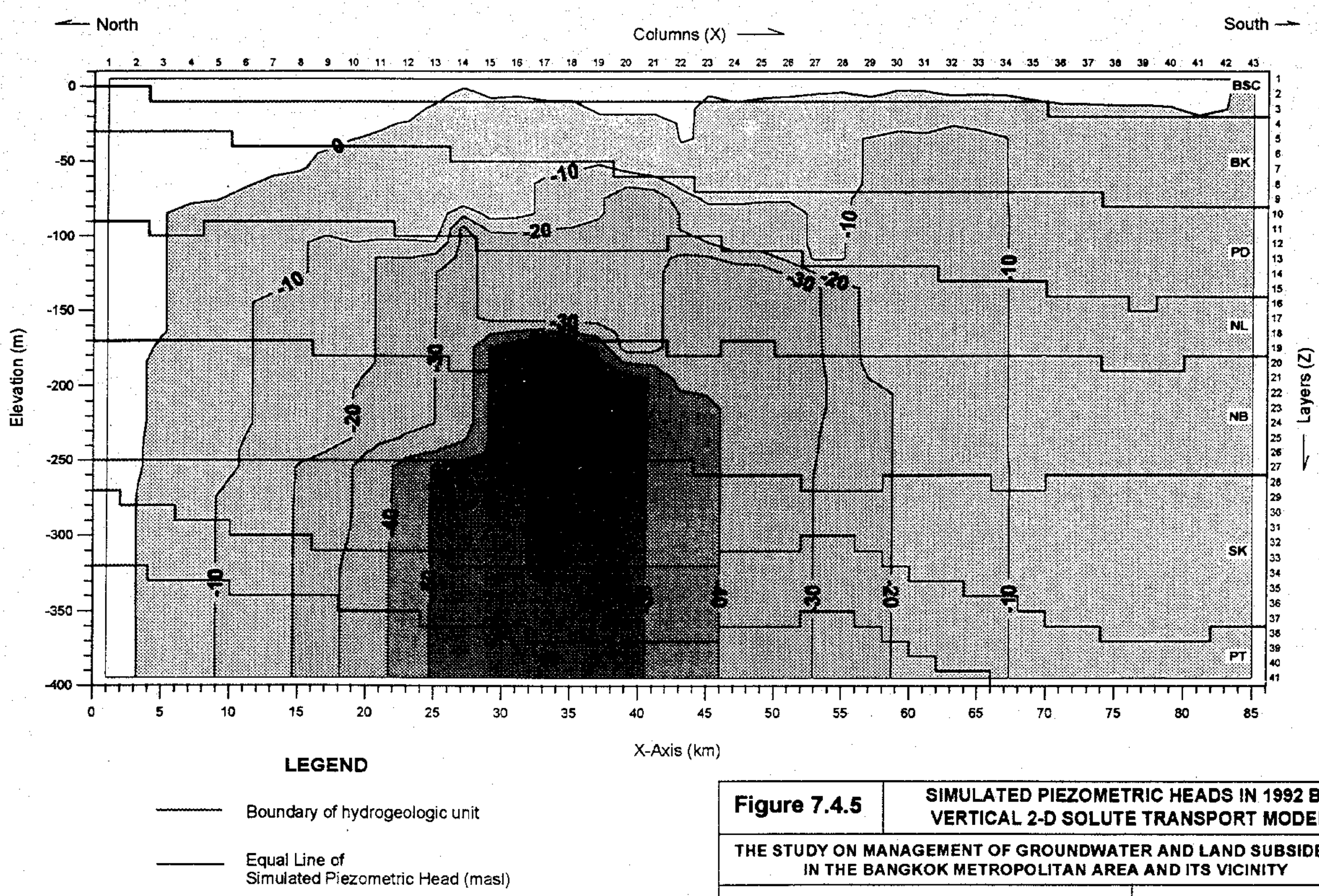

Figure 7.4.5 SIMULATED PIEZOMETRIC HEADS IN 1992 BY VERTICAL 2-D SOLUTE TRANSPORT MODEL

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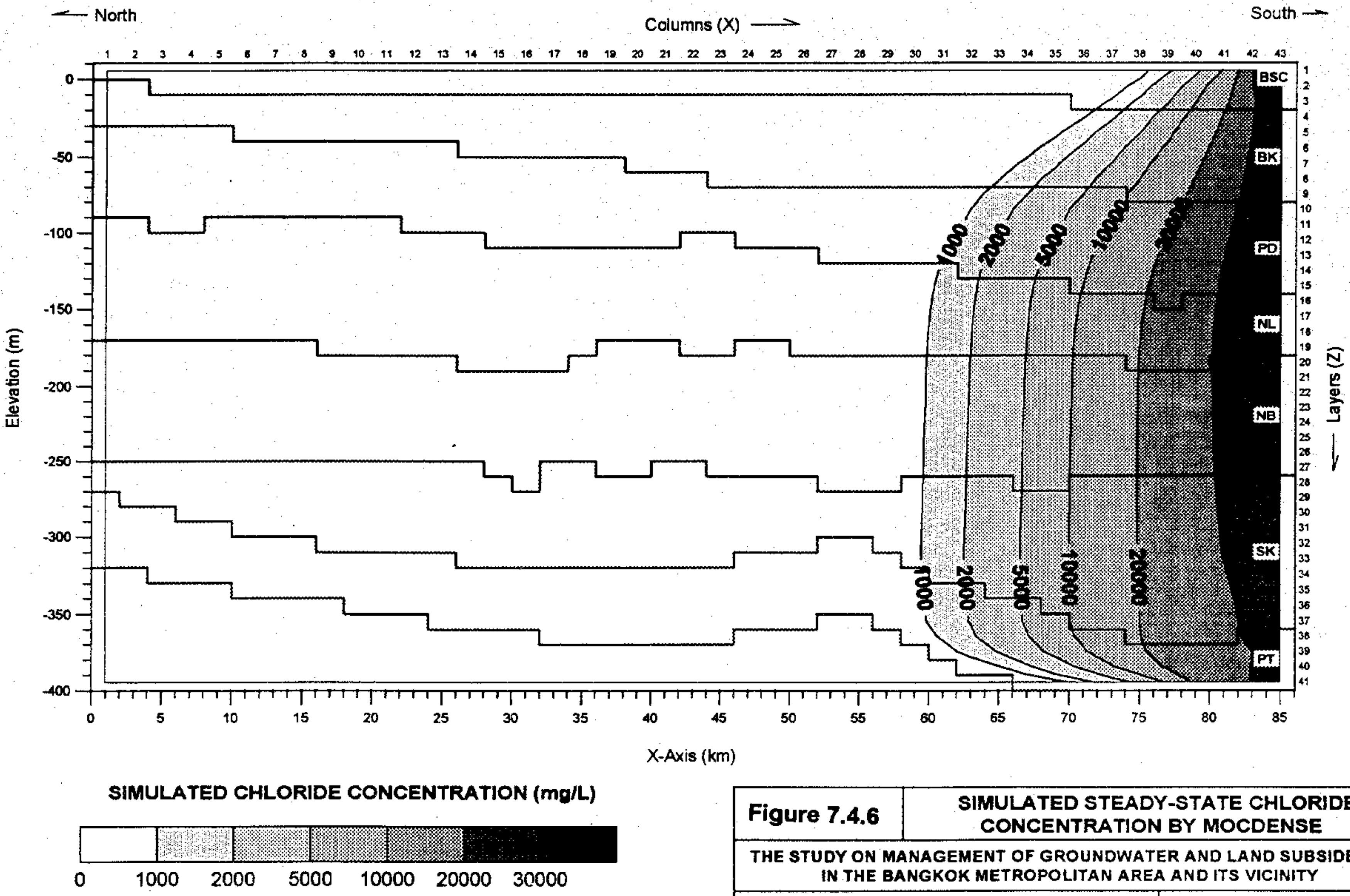

Figure 7.4.6	**SIMULATED STEADY-STATE CHLORIDE CONCENTRATION BY MOCDENSE**
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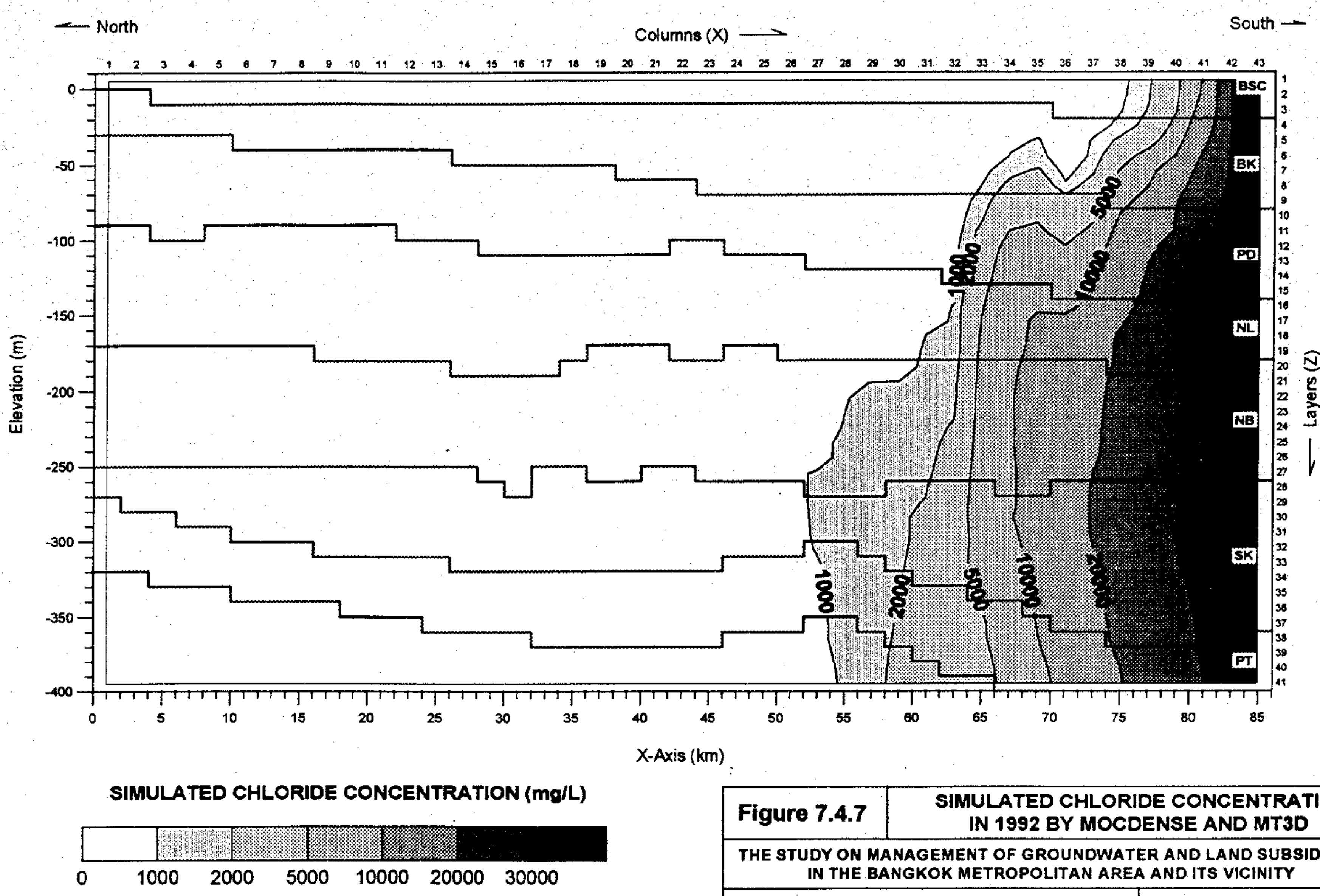

Figure 7.4.7 SIMULATED CHLORIDE CONCENTRATION IN 1992 BY MOCDENSE AND MT3D

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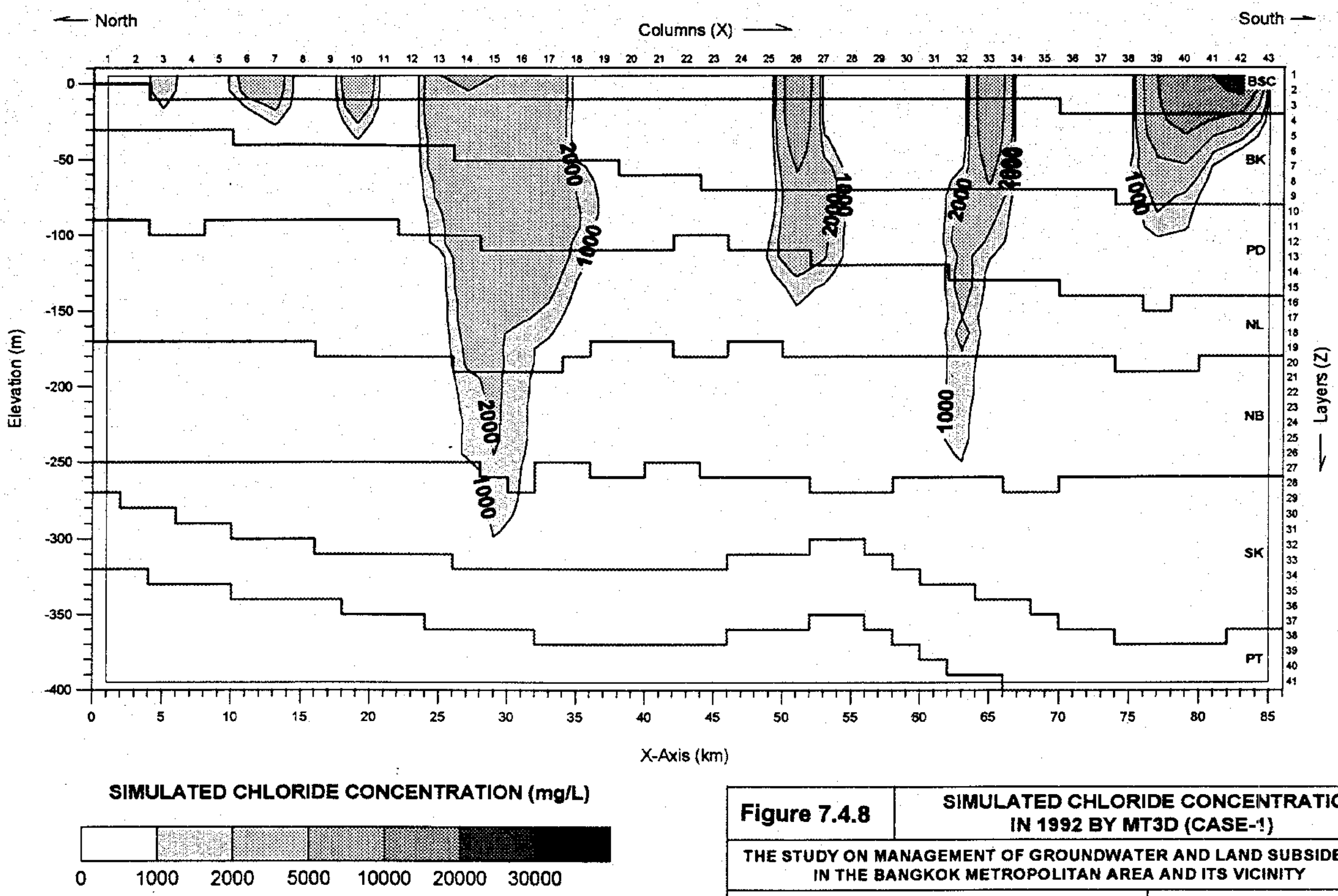

Figure 7.4.8 SIMULATED CHLORIDE CONCENTRATION IN 1992 BY MT3D (CASE-1)

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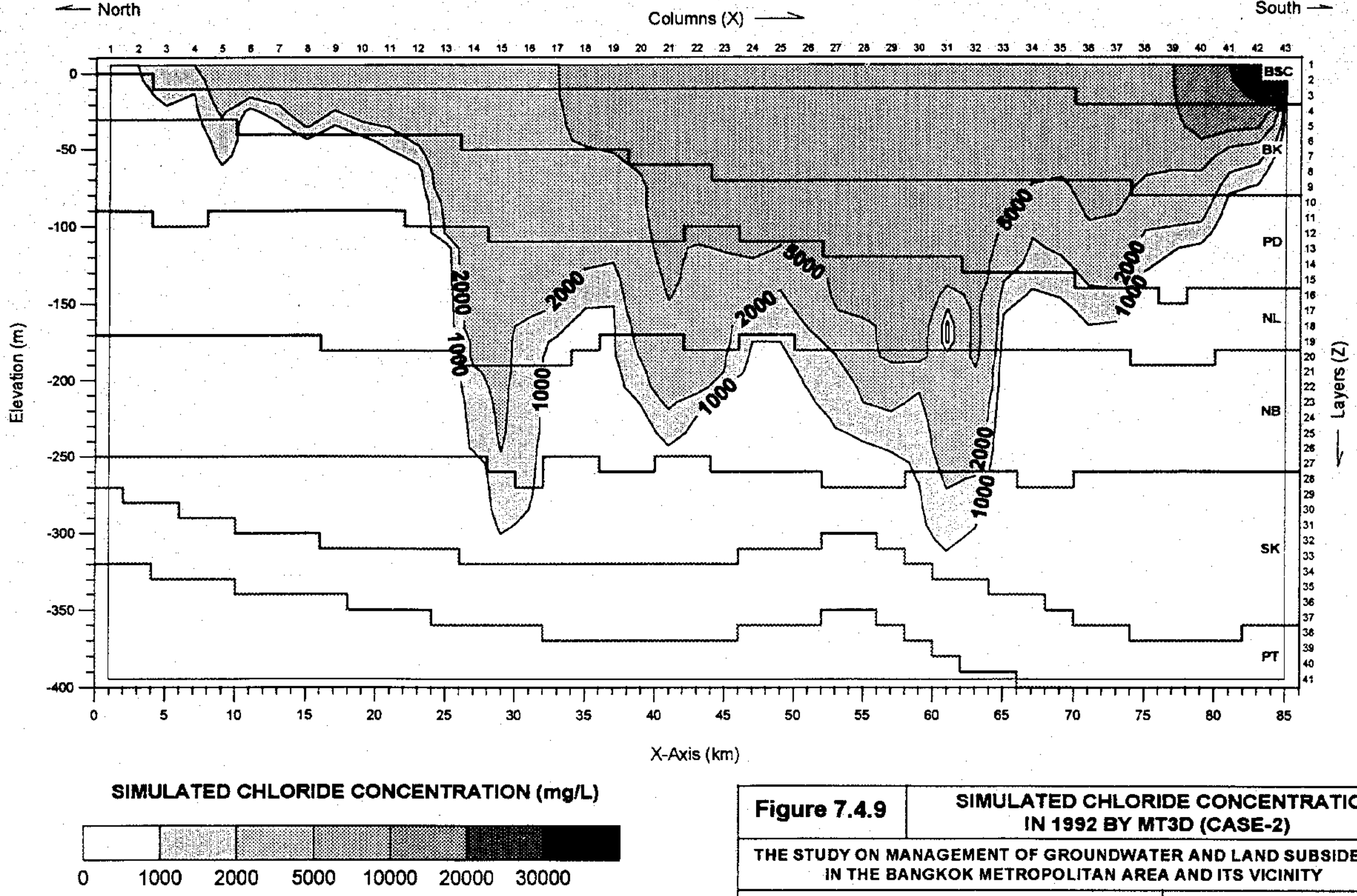

Figure 7.4.9	**SIMULATED CHLORIDE CONCENTRATION IN 1992 BY MT3D (CASE-2)**

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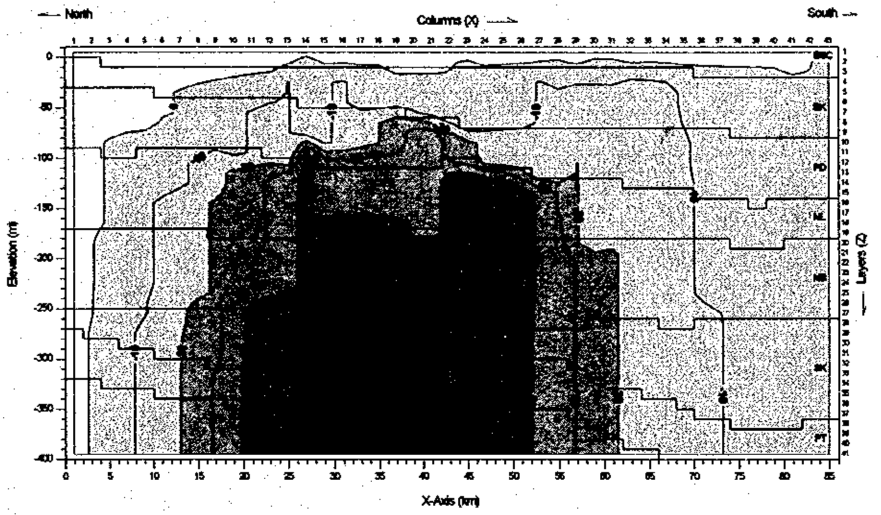
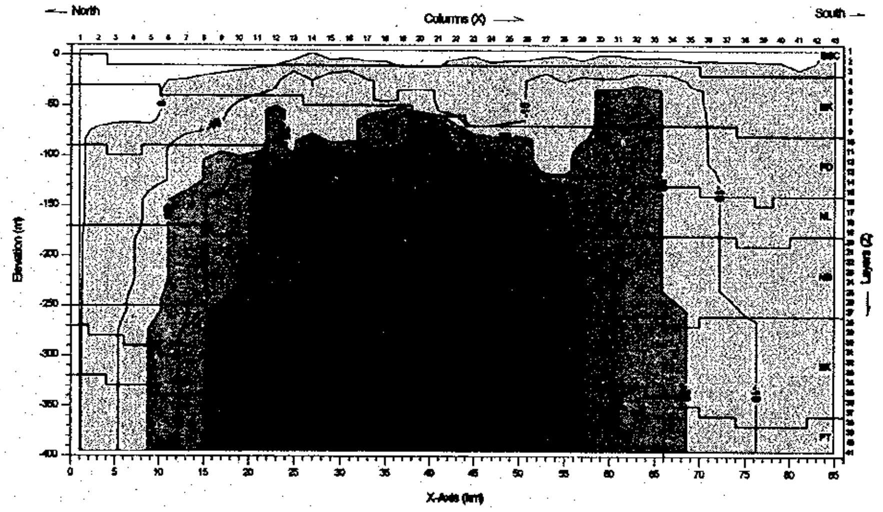
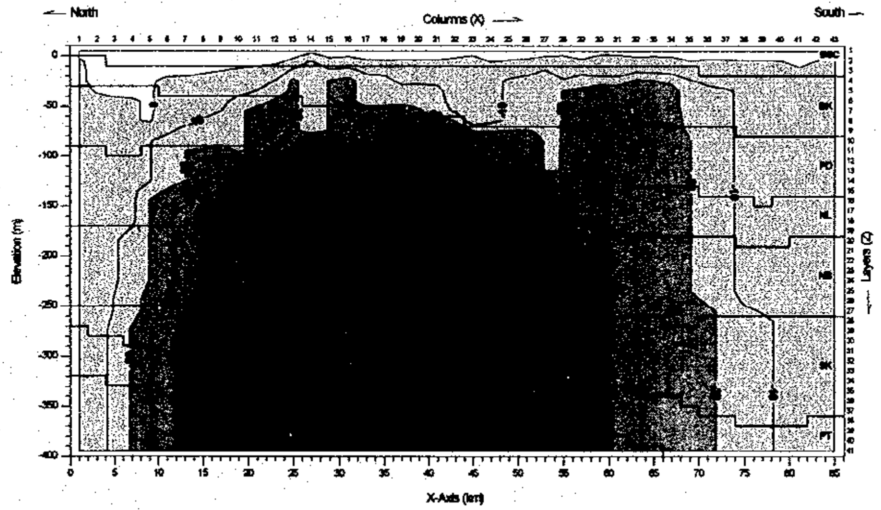


(a) 1997



(b) 2007



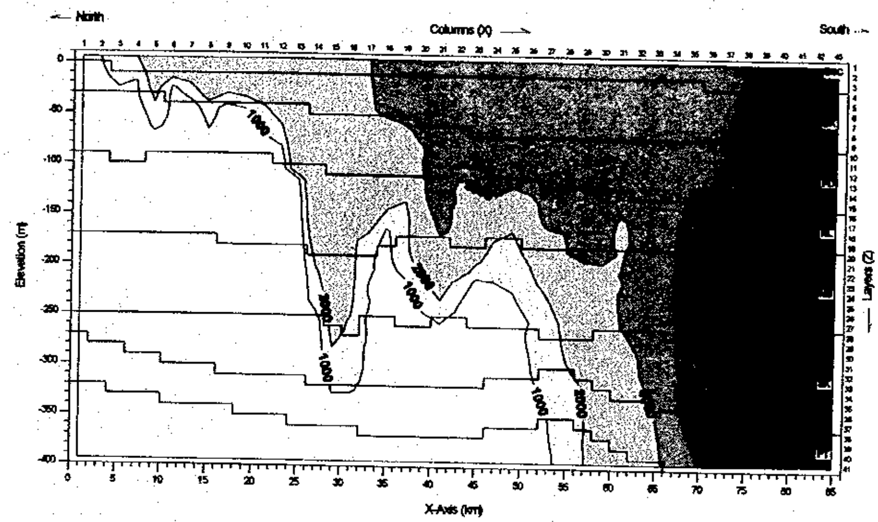
(c) 2017

LEGEND

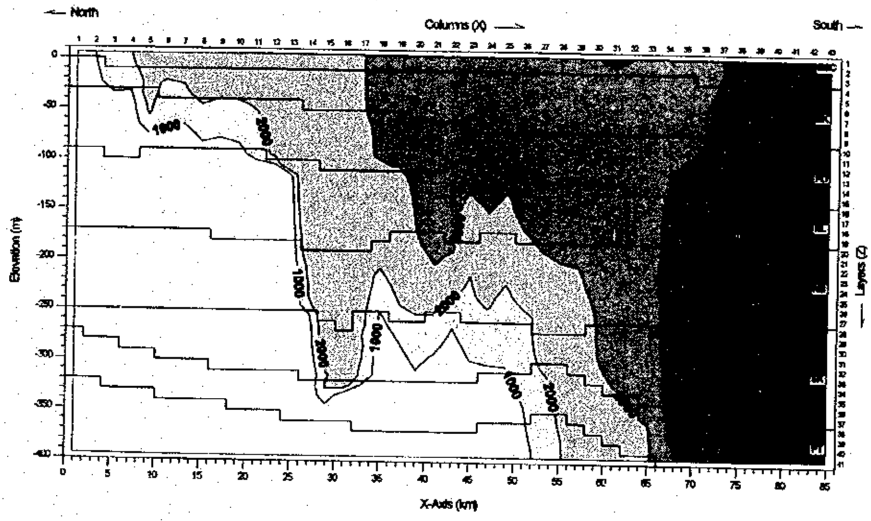
Boundary of hydrogeologic unit

Equal Line of Simulated Piezometric Head (msl)

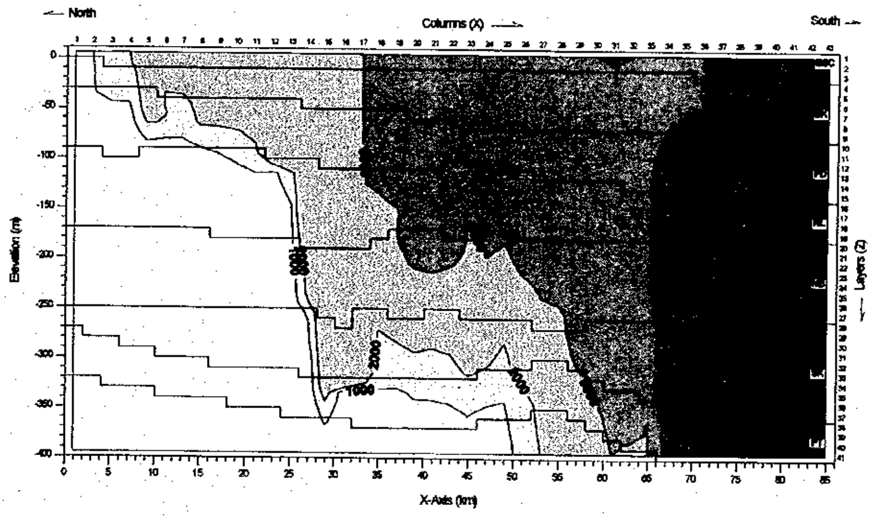
Figure 7.4.10 SIMULATED PIEZOMETRIC HEADS BY SCENARIO 1



(a) 1997



(b) 2007

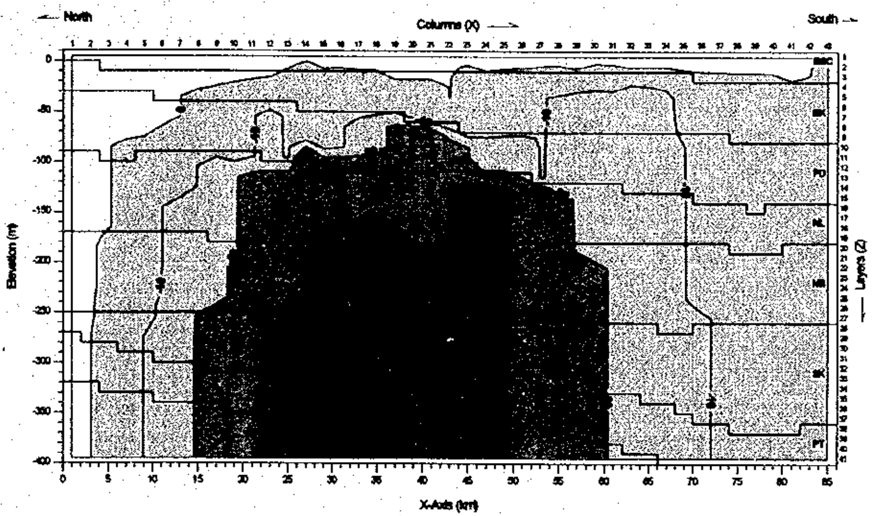


(c) 2017

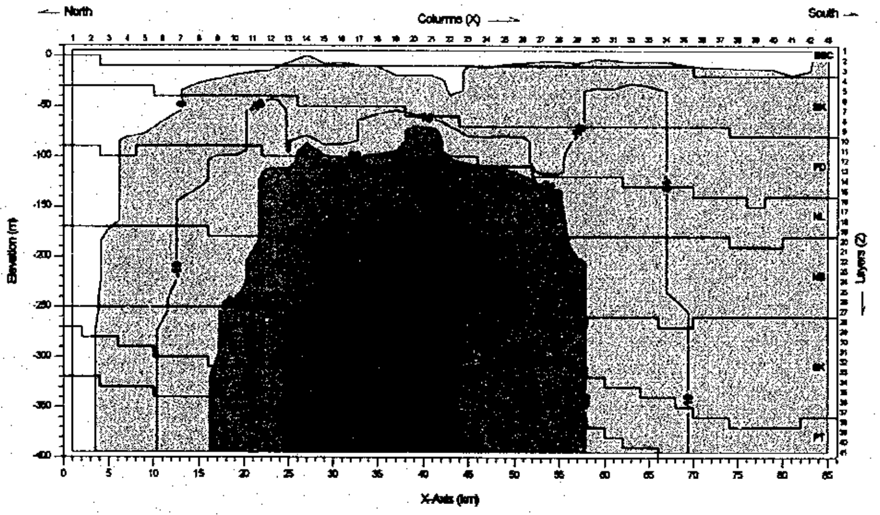
SIMULATED CHLORIDE CONCENTRATION (mg/L)

0	1000	2000	5000	10000	20000	30000

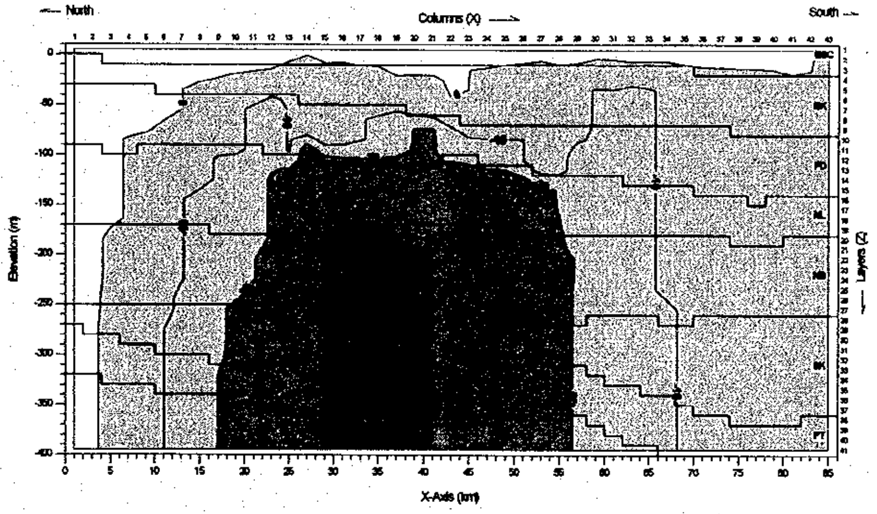
Figure 7.4.11 SIMULATED CHLORIDE CONCENTRATION BY SCENARIO 1



(a) 1997



(b) 2007



(c) 2017

LEGEND

——	Boundary of hydrogeologic unit
——	Equal Line of Simulated Piezometric Head (msl)

Figure 7.4.12

SIMULATED PIEZOMETRIC HEADS BY SCENARIO 7

THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY

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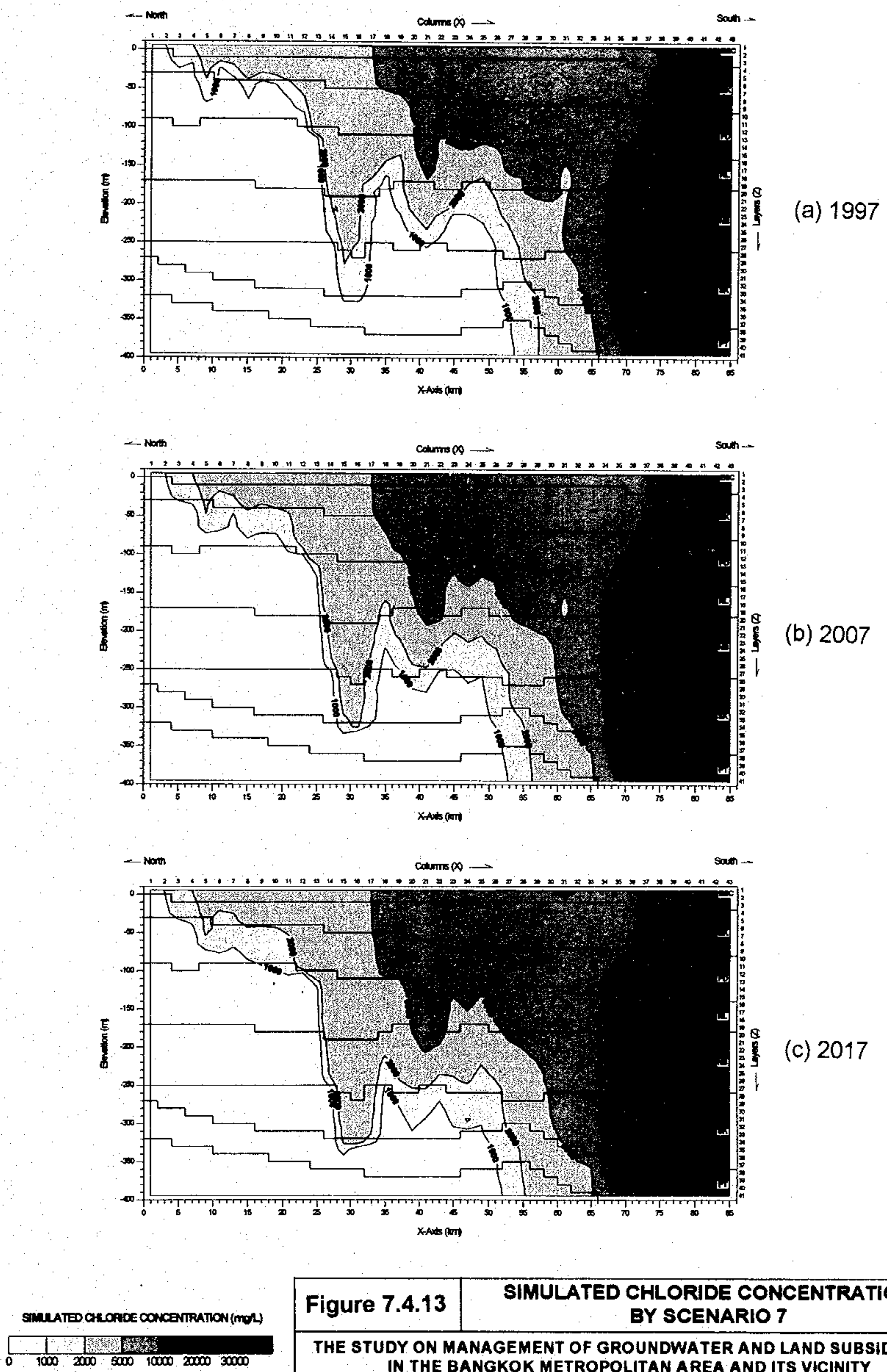

(a) 1997

(b) 2007

(c) 2017

Figure 7.4.13 SIMULATED CHLORIDE CONCENTRATION BY SCENARIO 7